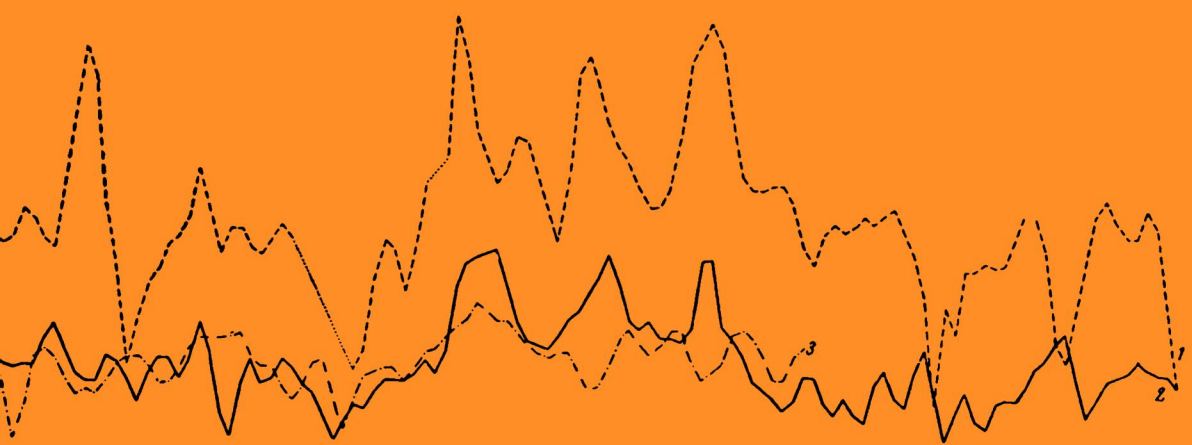
A. Kh. KHRGIAN, G.I. KUZNETSOV, AND A.V. KONDRAT'EVA

ATMOSPHETIC OZONE

D.I. Nasilov (Ed.)



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Results of Investigations in the International Geophysical Year

A.Kh. KHRGIAN, G.I. KUZNETSOV, AND A.V. KONDRAT'EVA

ATMOSPHERIC OZONE

(Issledovanie atmosfernogo ozona)

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Table of Contents

Chapter One. GENERAL FEATURES OF THE OZONE AMOUNT (A. Kh. Khrgian) 1

Chapter Two. OZONE OBSERVATIONS IN MOUNTAINS AND THE AEROSOL COMPONENT OF SCATTERING (G. I. Kuznetsov) 51

Chapter Three. VARIATIONS OF OZONE CAUSED BY VERTICAL MOTIONS IN THE ATMOSPHERE (A. Kh. Khrgian and A. V. Kondrat'eva) 56

Chapter Four. VARIATION OF THE TOTAL OZONE DURING TOTAL SOLAR ECLIPSE AND AN ATTEMPT AT ITS INTERPRETATION (A. Kh. Khrgian and G. I. Kuznetsov) . . . 66

Bibliography 71

Appendix I. MAXIMUM AND MINIMUM OZONE AT AROSA 75

Appendix II. MONTHLY OZONE AMOUNTS AT IGY STATIONS IN 1957—1959. 76

Appendix III. MAXIMUM AND MINIMUM OZONE AT IGY STATIONS IN 1957—1958. 78

Appendix IV. FLUCTUATION AMPLITUDES OF THE TOTAL OZONE AT IGY STATIONS IN 1957—1958 . 86

Appendix V. OZONE AMOUNT IN MOSCOW IN 1934—1935 . . 90

Explanatory List of Abbreviations. 90

TRANSLATOR'S NOTE

The Roman numerals I through XII in figures and tables in this translation are the original Russian notation for the twelve months of the year, January through December.

Chapter One

GENERAL FEATURES OF THE OZONE AMOUNT

RESULTS OF OBSERVATIONS

In the period from 1926 to 1956 the ozone observations were carried out by individual observers in different countries at arbitrary times. One of the achievements of the IGY was the setting up of systematic observations of atmospheric ozone in a considerable number of stations, all following a single program and using the same procedures.

A network of stations producing perfectly comparable and homogeneous observations suitable for statistical (climatologic) treatment and synoptic analysis of individual atmospheric processes was first organized in 1957. At last it became possible to correlate the ozone measurements with the observations of the atmosphere and atmospheric circulation on a planetary scale.

Figure 1 is a map showing the distribution of the IGY ozone stations. There are 50 stations in the northern hemisphere, 11 in the southern (Table 1). The ozone in the southern hemisphere remains insufficiently studied to this day. In the northern hemisphere, the highest "density" of coverage is between 40 and 60° of latitude (23 stations); the tropical zone between 15°N and 15°S is represented only by two stations, while in the open ocean observations were carried out on "insular" stations only — Torishima, Marcus, Mauna Loa, Macquarie, and Kerguelen. Unfortunately no data are available for the Atlantic Ocean, although the Commission for Atmospheric Ozone maintained a station on the Azores Islands.

Nine stations are at elevations of over 1000 m above sea level: Mauna Loa (3398 m), Kodaikanal (2344 m), El'brus (2146 m), Arosa, Quetta, Abastumani, Srinagar, Tamanrasset, and Mount Abu.

Table 4 shows that only 31 stations carried out regular observations during the entire IGY (with gaps in records not exceeding two months), and that on some stations the observations were begun only in 1958 (Green Bay, Sapporo, Kagoshima, Torishima, Quetta, Marcus, Leopoldville, Oazis, Dumont d'Urville).

The main contribution to systematic ozone observations during the IGY was due to USSR (11 stations), USA (7 stations), England and Japan (5 stations each), India (4 stations and a short series of observations at Benares), France (4 stations and a short series of observations at Port-aux-Français), Italy and Canada (4 stations each).

The observations in the polar regions were often restricted to the daylight period. Nocturnal observations were typically carried out on the full moon, and thus could not replace ordinary daytime observations. The data available had to be sifted to allow for this lack of equivalence.

The scarcity of observations in the southern hemisphere, and in particular in Antarctica, is especially regrettable because the variation of the ozone distribution there is distinctly different from that observed in the northern hemisphere.

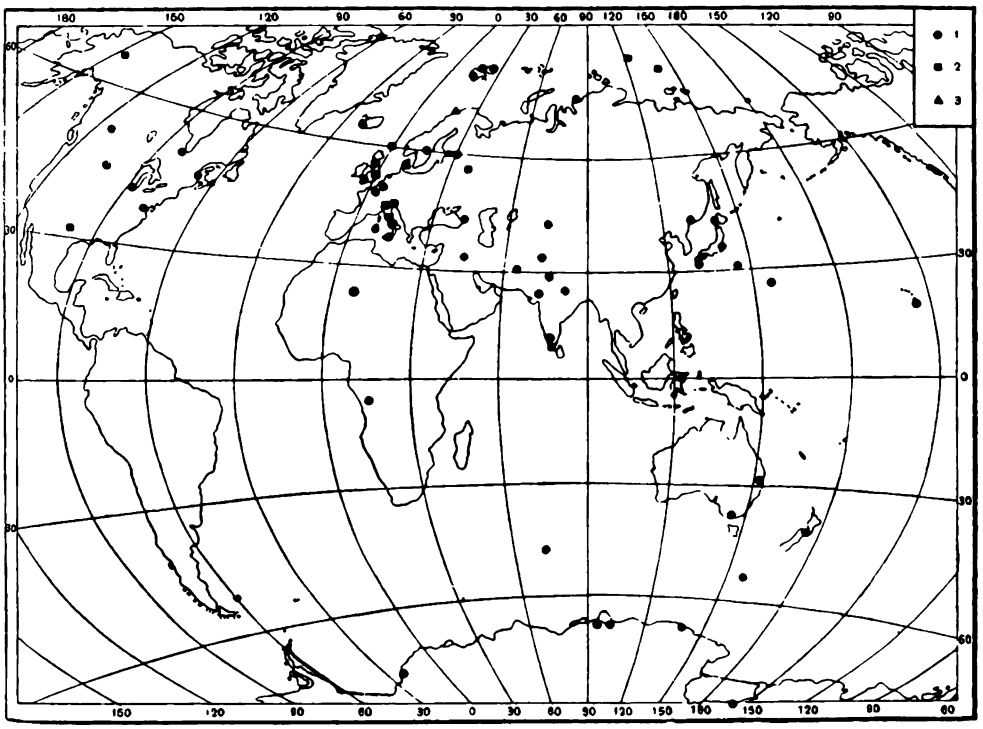

FIGURE 1. Network of ozone stations:
1) IGY stations; 2) stations which operated before and during IGY; 3) stations operative between the years 1925—1944.

A Dobson spectrophotometer — the most versatile instrument for ozone measurements — was the standard apparatus of the IGY observations. There are over 50 spectrophotometers of this kind in the world to-day, but some of them, e.g., the spectrophotometer in Azores, remained inoperative during the IGY. The results obtained with alternative instruments were invariably compared with the spectrophotometric findings. In USSR, in particular, the readings of another standard IGY instrument (the Rodionov electrophotometer with filters /16/) were compared with the results obtained with the Dobson spectrophotometer at Voeikovo (near Leningrad).

According to the recommendations of the International Ozone Commission (IOC), the following wavelengths in the solar (or the lunar) spectrum were employed in spectrophotometric observations:

Symbol	*A*	*B*	*C*	*D*	*C'*
Wavelength, Å	3055 –3254	3088 —3291	3114—3324	3176—3398	3324—4536

TABLE 1. IGY ozone stations

No.	Station	Country, territory	Coordinates		h, m	Locality
			φ	λ		
Northern Hemisphere						
1	SP-6	USSR	81—84°	148—130°		Ice-borne drifting station
2	Alert	Canada	82°30'	62°20' W		Archipelagic island
3	Kheis Isl.	USSR	80 37	58 03		Near the ocean
4	Murchison	Spitsbergen, Norway	80 03	18 18		Near the ocean
5	Longyearbyen	Spitsbergen, Norway	78 13	15 35		Archipelagic island
6	Resolute Bay	Canada	74 43	94 59 W		Archipelagic island
7	Dikson	USSR	73 30	80 24		Offshore island
8	Tromsö	Norway	69 40	18 57		Near the ocean
9	Reykjavik	Iceland	64 8	21 25 W		Near the ocean
10	Lerwick	UK	60 28	1 11 W		Near the ocean
11	Voeikovo	USSR	59 57	30 42		Near the coast of a bay
12	Uppsala	Sweden	59 52	17 38		Continent
13	Aarhus	Denmark	56 01	10 13		Coast of a strait
14	Moscow	USSR	55 44	37 38		Continent
15	Eskdalemuir	UK	55 19	3 12		Near seashore
16	Edmonton	Canada	53 34	113 31	658	Continent
17	Potsdam	German Democratic Republic	52 24	13 06		Continent
18	Oxford	UK	51 45	1 11		Continent
19	Moosonee	Canada	51 16	80 39		Coast of a bay
20	Uccle	Belgium	50 51	4 22		Near seashore
21	Camborne	UK	50 13	5 19		Near the ocean
22	Paris (Montsouris)	France	48 49	2 20		Continent
	Magny-les-Hameaux		48 44	2 04		Continent
23	Caribou	Maine, USA	46 50	68 11 W		Near the coast of a bay
24	Arosa	Switzerland	46 47	9 41		Continent
25	Bismarck	N. Dakota, USA	46 47	100 38 W	512	Continent
26	Green Bay	Wisconsin, USA	44 31	88 00 W		Continent, on the coast of a lacustrine bay
27	El'brus	USSR	43 5	42 5	2146	Continent
28	Vladivostok	USSR	43 47	132 02		Seashore
29	Alma-Ata	USSR	43 16	76 57	851	Continent
30	Sapporo	Japan	43 03	141 20		Near seashore
31	Vigna di Valle	Italy	42 04	12 12		Near seashore
32	Abastumani	USSR	41 45	42 50	1600	Near seashore
33	Naples	Italy	40 52	14 15		Seashore
34	Elmas	Sardinia, Italy	39 15	9 03		Seashore
35	Washington	D. C., USA	38 54	77 03 W		Near the ocean
36	Messina	Sicily, Italy	38 12	15 33		Coast of a strait
37	Tateno	Japan	36 03	140 08		Near the ocean
38	Srinagar	Kashmir, India	34 05	74 50	1586	Continent
39	Habbaniyah	Iraq	33 22	43 34		Continent
40	Fort Worth	Texas, USA	32 43	97 15 W		Continent
41	Kagoshima	Japan	31 38	130 36		Coast of an oceanic bay
42	Torishima Isl.	Japan	30 29	140 18		Small oceanic island
43	Quetta	W. Pakistan	30 11	66 57	1677	Continent
44	Delhi	India	28 38	77 13		Continent
45	Benares	India	25 19	83 00		Continent
46	Mount Abu	India	24 36	72 45	1203	Continent
47	Marcus Isl.	Japan	24 17	153 58		Small oceanic island

TABLE 1. (cont.)

No.	Station	Country, territory	Coordinates*		h*, m	Locality
			φ	λ		
48	Tamanrasset	Algeria	22 48	5 31	1395	Continent
49	Mauna Loa	Hawaii, USA	19 29	155 36 W	3398	Large oceanic island
50	Kodaikanal	Madras, India	10 14	77 28	2344	Continent
Southern Hemisphere						
51	Leopoldville	Congo	4 22 S	15 15		Continent
52	Brisbane	Australia	27 28	153 02		Near the ocean
53	Aspendale	Australia	38 02	145 06		Near the ocean
54	Wellington	New Zealand	41 17	174 46		Near the ocean
55	Port-aux-Français	Kerguelen, France	49 21	70 13		Oceanic island
56	Macquarie Isl.	Australia	54 29	158 57		Oceanic island
57	Oasis	Antarctica (USSR)	66 16	100 44		Near the ocean
58	Mirnyi	Antarctica (USSR)	66 33	93 00		On the coast of the ocean
59	Dumont d'Urville	Antarctica (France)	66 40	140 01		On the coast of the ocean
60	Halley Bay	Antarctica (UK)	75 31	26 36 W		Seashore
61	Little America	Antarctica (USA)	78 11	162 10 W		On the coast of the ocean

* Longitude E unless otherwise indicated (W). Heights indicated only for stations with elevations of over 500 m above sea level.

Table 2 lists the code notations for different pairs of these wavelengths.

When the sun or the moon were low in the sky, the longer wavelengths were generally measured, because the short-wave region of the spectrum was extremely weak under these conditions, even if focusing of the image was tried.

TABLE 2. Code notations for pairs of wavelengths

Code λ	Wavelengths**	Code λ	Wavelengths**
0	*AD*	4	*AD*
1	*BD*	5	*BD*
2	*CD*	6	*CD*
3	*CC'*	7*	*C*

* 8 — 9 — other wavelengths.

** Focused image.

In our sample of data from 15 non-Soviet stations (Resolute Bay, Tromsö, Uppsala, Aarhus, Eskdalemuir, Oxford, Moosonee, Arosa, Green Bay, Sapporo, Srinagar, Torishima, Kodaikanal, Leopoldville, Little America) for January and July 1958, the different wavelength pairs featured with different percentage frequencies (Table 3). Observations on the moon were generally made taking $\lambda = 6$ (Leopoldville), $\lambda = 6, 7, 8$ (Resolute Bay), and occasionally $\lambda = 4$. In the Soviet Union the *CC'* pair was used in all the observations ($\lambda = 3$).

TABLE 3. Percentage frequency of different wavelength pairs

Code λ	0	1	2	3	4	5	6	7	8	9
Wavelengths	*AD*	*BD*	*CD*	*CC'*	*AD*	*BD*	*CD*	*C*	—	—
Number of observations, %	56	1.5	—	29	1	0.5	7	1	1.5	1.5

The IOC had suggested ozone observations on the diffuse light of clear or cloudy sky, as well as on the direct light of the sun or the moon. Each station was expected to make a comparison between direct- and scattered-light observations for different heights of the sun and to construct a graph enabling the ozone amount x to be determined by observations on clear and cloudy sky. If these graphs were available, virtually uninterrupted daytime observations could be made. For example, the observations at the Italian observatory of Vigna di Valle on clear and overcast sky gave an almost continuous and smooth curve, and the findings of this station could be applied in further treatment.

In the 15 non-Soviet stations sampled, 52% of the observations were made on the direct sun, 5.5% on the moon, 6.5% on clear zenith sky, 36% on cloudy sky. In the USSR all observations were carried out on direct solar light.

After preliminary treatment, the findings of the ozone stations all over the world were recorded on standard forms and transmitted to International Data Centers. The Moscow International Data Center B accumulated the results of nearly all the ozone stations in the world for the years 1957—1958. The 1959 data were received in Moscow after an unfortunate delay and were only partly incorporated in our study.

In most of the stations, the total ozone amount x was measured 3—5 times daily, every time on the hour (GMT). From these data we calculated the diurnal average x, which was adopted as a more reliable characteristic of the ozone amount than the individual observations. Some stations (e.g., the French) reported only the x-value for the local noon, which for lack of any alternative had to be accepted on the same basis as the more accurate daily means of the other countries. In exceptionally fine weather, some stations carried out as many as 5 to 20 observations daily. These "protracted" or "detailed" observation of the single equatorial station in Leopoldville and of Soviet stations (SP-6, Kheis Island, and others) are of particular significance. Meteorological and astronomical stations should be urged to carry out and publish detailed observations of ozone whenever atmospheric conditions are favorable. Particular emphasis on detailed observations should be laid during the International Quiet Sun Year (IQSY). Detailed ozone observations should be organized during the large-scale advances of arctic air at the end of the winter or in spring, in periods of the enhanced meridional circulation in summer, and possibly also when tropic air advances to the temperate zone.

Very few countries have published new results of ozone observations since the end of the IGY. USSR /7/ and France /52/ are in this select company. A highly valuable contribution was made by K. R. Ramanathan, IOC chairman, who summarized the monthly x-values according to the findings of stations all over the world for the years 1957—1959 and distributed his report in mimeographed form to the members of the Commission as early as the beginning of 1960. The author regrettably failed to specify the averaging technique adopted. It is from this report that we borrowed the monthly x-values of non-Soviet stations for 1959. A. Vassy's data /52/, besides the total ozone amount, also contain information on the surface ozone in the neighborhood of Paris (Val Joyeux) for the years 1958—1959 and some observations of the vertical ozone distribution by the umkehr method and with radio sondes.

TABLE 4. Ozone observations from 1925 to 1957

No.	Station (country, territory)	Observations begun	Data published for the years
1	Oxford (UK)	February 1925	
2	Arosa (Switzerland)	July 1925	1925—1958
3	Tromsö (Norway)	July 1935	1935—1959
4	Valentia (Ireland)	September 1926	1926—1927
5	Lindenberg (Germany)	July 1926	1926—1927
6	Lerwick (UK)	July 1926	1926—1927, 1957—1959
7	Abisko (Sweden)	July 1926	1926—1927, 1934—1935
8	Marseille (France)	January 1927	1927—1928
9	Christchurch (New Zealand)	August 1928	1928—1929
10	Montezuma (Chile)	November 1926	1926—1927
11	Kodaikanal (India)	September 1928	1928—1929, 1957—1959
12	Helwan (Egypt)	September 1928	1928—1929
13	Table Mountain (USA)	August 1928	1928—1929
14	Longyearbyen (Norway)	July 1929	1929, 1957—1959
15	Canberra (Australia)	February 1929	1929—1932
16	Shanghai (China)	January 1932	1932—1944
17	Bombay (India)	October 1936	1936—1938
18	Moscow (USSR)*	February 1934	1934—1935
19	New York (USA)	January 1941	1941
20	Pasadena (USA)	September 1939	1939—1940
21	Potsdam (German Democr. Rep.) /30/	September 1941	1941—1945
22	Edmonton (Canada) /26/	August 1950	1950—1952
23	Kabul (Afghanistan) /35/	December 1950	1950—1951
24	Tateno (Japan)	July 1955	1955—1956
25	Dombås—Oslo (Norway) /50/	March 1940	1940—1949
26	Washington (USA) /23/	February 1948	1948—1950, 1954—1956
27	College (USA) /20/	January 1952	1952
28	Albuquerque (USA) /51/	January 1954	1954
29	Bismarck (USA) /51/	January 1954	1954—1956
30	Fort Worth (USA) /51/	January 1954	1954—1955
31	Delhi (India) /33/	November 1945	1945—1947, 1955—1957
32	Ahmedabad (India) /33/	January 1955	1955
33	Mount Abu (India) /33/	January 1955	1955—1957
34	Gulmarg (India) /33/	July 1955	1955—1956
35	Srinagar (India) /33/	April 1957	1957

* A table of Moscow observations for 1934—1935 will be found in Appendix V.

Note. The data of British stations from 1950 to June 1957 (Aldergrove, Camborne, Downham Market, Eskdalemuir, Hemsby, Lerwick, Oxford), the observations at Aarhus (Denmark) for the years 1940—1943 and 1951—1957, in Uccle (Belgium) for 1951—1957, Santa Maria (Azores) for 1951—1956, and in Uppsala (Sweden) for 1951—1957 have not been published. The New York observations for 1941—1944 and the Flagstaff, Arizona observations for 1954—1956 are available in service reports only.

The 1957—1958 figures for the USSR were borrowed from the tables available at the Moscow International Data Center B (the treatment and the interpretation were uniform for all the Soviet and non-Soviet data). Our mean ozone values may therefore somewhat differ from the daily averages published in /7/, since the latter are frequently based on more extensive initial data than the results listed in standard tables. The 1959 monthly averages for the USSR were borrowed from /7/.

The monthly x-values for all the stations were calculated by averaging the daily means (see Appendix II).

It has been suggested by the IOC that the data from Caribou (USA) and Tamanrasset (Algeria) are insufficiently reliable, which is particularly obvious if we consider the wide spread of the x-values from Caribou. The Tamanrasset data are rejected because some of the x-values are exceedingly small, and the total ozone trend during the entire year seems to be suspiciously low. We will show, however, that high air temperatures are on the whole associated with low x-values, which may probably explain the apparent ozone anomaly on this Sahara station. The noon x-values in Sahara are steadily less than 0.16 cm.

The data for Voeikovo (USSR) and Aarhus (Denmark) are somewhat higher than the corresponding results for nearby stations. The Sapporo data, which appear to be unacceptably high in comparison with the values for continental stations, are corroborated by the Japanese observatory of Tateno. The zonal gradients of all the meteorological elements are apparently very steep in this part of the Far East on account of the continental effect and jet currents. This may explain the high values of x for Sapporo.

It is interesting to compare the IGY network with the list of stations which have operated before 1957 (see Table 4, which is borrowed from /21/ and augmented by us). Only three stations in the world can be credited with uninterrupted, long-term observations of the total ozone amount x: these are Arosa, Oxford, and Tromsö. Nothing but their data are available for analyzing the secular ozone variation, its relation to the solar cycle, and other long-term phenomena of this kind.

The stations listed in Table 4 for the period between 1925 and 1941 provide cumulative material for a total duration of 62 years. One of the deficiencies of this extensive body of data is that most of the stations are located in Europe. Another unfavorable factor is that the stations changed and the continuity of observations was not preserved. For example, only three of the stations listed in Table 4 (Lerwick, Spitsbergen, and Kodaikanal) operated during the IGY. It is only the few stations commissioned after 1950 (Potsdam, Tateno, Edmonton) that provide a reliable link between the IGY and the previous observation periods.

In conclusion note that the new ozone absorption coefficients proposed by Vigroux /53/ and adopted by the IOC for IGY ozone calculations give x-values which are on the average a factor of 1.35 higher than the old figures. This point must be remembered in comparing the ozone amounts before and after 1957. In the extensively studied 40—60° zone, the new data are on the whole in satisfactory agreement with the older material used by Götz in 1944 /13/, provided that the factor of 1.35 is taken into consideration. This overall comparison is of very limited value, but "collective standards" of this kind are often used in meteorology.

STATISTICAL ACCURACY OF ATMOSPHERIC OZONE OBSERVATIONS

When the observations are completed, the researcher should establish the accuracy of the various statistical characteristics (e.g., the monthly or the yearly averages, etc.) which can be derived from the observational data. Here "errors" include the random errors of observations, as well as the natural variability of the ozone amount, dependent on meteorological, solar, and other factors.

TABLE 5. Total ozone in Arosa x, 10^{-3} cm (old units)

Year	Jan.	Feb.	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Yearly average
1926							221	215	200	194	209	231	
1927	255	258	267	265	270	248	238	223	217	200	202	229	239
1928	230	231	246	254	265	234	218	209	204	190	199	222	225
1929	247	283	252	295	260	245	—	—	—	—	—	—	—
1930	—	—	—	—	—	—	—	211	—	—	—	—	—
1931	—	—	—	—	—	—	—	221	238	201	204	214	—
1932	226	246	262	278	255	246	237	213	208	210	208	200	232
1933	253	257	282	269	275	264	237	226	219	222	221	239	247
1934	237	228	277	254	258	252	233	228	200	204	207	211	232
1935	235	275	260	271	265	227	235	221	205	196	213	222	235
1936	233	273	281	271	264	249	233	224	215	220	211	218	241
1937	245	249	279	270	259	248	230	229	214	201	199	252	240
1938	239	261	231	277	272	238	231	231	210	199	203	212	234
1939	227	242	272	246	270	240	235	222	204	216	202	220	233
1940	274	283	295	303	285	274	245	229	220	207	214	239	256
1941	256	279	294	289	295	255	247	238	217	213	219	219	252
1942	283	298	264	288	266	246	231	219	202	193	212	222	244
1943	239	242	272	257	247	249	238	215	199	208	215	227	234
1944	213	258	272	255	247	248	227	217	207	208	212	227	233
1945	267	255	255	264	266	249	233	232	211	205	210	222	239
1946	238	249	269	256	251	243	225	218	197	207	211	225	232
1947	271	281	278	261	256	241	237	230	218	210	198	221	242
1948	242	262	246	257	250	245	244	221	212	200	203	228	234
1949	236	258	267	253	262	251	238	228	202	194	210	208	234
1950	250	258	259	270	265	251	229	224	208	205	204	241	239
1951	240	284	294	281	271	258	235	228	211	212	198	221	244
1952	267	271	290	273	272	254	242	227	225	211	215	236	249
1953	238	266	264	270	270	254	232	225	208	—	190	—	237
1954	—	—	265	294	275	256	246	233	217	203	207	202	242
1955	224	265	282	264	256	249	241	236	213	208	198	220	238
1956	237	278	264	274	253	249	227	215	200	198	199	216	234
1957	237	249	246	256	266	244	231	225	212	196	207	228	233
1958	256	248	290	295	263	260	248	232	214	218	215	230	247
1959	259	257	257	272	272	261	240	232	221	208	210	230	243
Many-year average	245.1	261.5	268.8	270.4	264.6	249.3	235.0	224.2	211.2	205.1	207.1	223.6	238.8

TABLE 6. Total ozone in Tromsö x, 10^{-3} cm (old units)

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly average
1935	—	—	—	—	—	—	233	199	196	167	(189)	(190)	—
1936	(171)	(198)	297	308	275	252	237	216	205	195	—	—	224
1937	249	(329)	316	263	249	237	216	205	203	(205)	(169)	(201)	237
1938	—	—	290	313	281	252	216	217	211	197	—	—	233
1939	—	—	270	275	273	253	223	201	203	212	217	184	233
1940	282	320	324	327	288	271	253	240	220	207	178	167	256
1941	259	326	345	326	303	275	233	225	211	215	199	218	266
1942	246	339	362	317	303	260	239	228	220	212	176	155	255
1943	206	292	304	303	295	253	234	226	208	194	177	124	235
1944	132	279	296	294	281	247	220	215	216	209	184	133	225
1945	166	274	293	318	292	263	222	221	217	211	165	130	231
1946	145	269	309	313	283	245	220	211	201	182	151	—	224
1947	123	282	301	297	286	253	233	220	215	212	153	108	231
1948	186	256	278	298	287	257	229	227	210	200	181	—	—
1949	—	245	271	309	301	—	—	—	—	—	—	—	—
1957	—	—	—	—	—	—	229	226	216	205	197	202	—
1958	242	353	345	315	295	268	231	213	214	207	221	217	260
1959	254	279	300	327	277	273	235	223	207	197	208	—	253
Many-year average	205	289	306	306	286	257	230	218	210	202	184	169	240

TABLE 7. Total ozone in Zi-ka-wei x, 10^{-3} cm (old units)

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov	Dec.	Yearly average
1932	212	243	262	249	241	240	226	229	233	226	221	219	233
1933	254	263	262	254	255	258	232	239	231	211	206	231	242
1934	248	251	268	249	248	240	233	225	221	216	197	218	234
1935	253	275	262	262	262	244	224	224	228	219	208	224	240
1936	265	269	275	269	267	(209)	228	232	230	223	214	221	242
1937	234	252	258	266	265	246	234	222	222	218	222	237	240
1938	—	267	266	280	261	245	233	226	215	215	220	235	(242)
1939	236	239	256	267	259	246	235	220	228	224	223	235	239
1940	256	268	282	283	265	267	235	238	228	223	222	234	250
1941	246	250	258	268	267	260	238	231	231	233	230	232	245
1942	236	265	259	279	277	252	240	222	223	226	227	230	245
Many-year average	244	258	264	266	261	246	232	228	226	221	218	229	241

The total ozone observations of three observatories span a sufficiently long period for the study of statistical properties.

1. The observations in Arosa (Switzerland) were carried out from July 1926 to June 1929 and then from August 1931 to this day, with brief interruptions in October and December 1953 and in January—February 1954. In practice, we have here a continuous 1931—1959 series (28 years) supplemented by a three-year series in 1926—1929. Götz, the outstanding world authority on ozone, organized and took active part in these observations. The measurements were made with the greatest care on the direct sun. The data for Arosa were borrowed from Dütsch and Perl /44/ for the years 1926—1958 and augmented with recent data for 1959 (Table 5).

TABLE 8. Deviation Δx of the total ozone from the many-year monthly values for Arosa, 10^{-3} cm (old units)

Year	Jan	Feb.	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec.	Annual
1926	—	—	—	—	—	—	—14	— 9	—11	—11	+ 2	+ 7	—
1927	+10	— 3	— 2	— 5	+ 5	— 1	+ 3	— 1	+ 6	— 5	— 5	+ 5	0
1928	—15	—30	—23	—16	0	—15	—17	— 5	— 7	—15	— 8	— 2	—14
1929	+ 2	+22	—17	+25	— 5	— 4	—	—	—	—	—	—	—
1930	—	—	—	—	—	—	—	—13	—	—	—	—	—
1931	—	—	—	—	—	—	—	— 3	+27	— 4	— 3	—10	—
1932	—19	—15	— 7	+ 8	—10	— 3	+ 2	—11	— 3	+ 5	+ 1	—24	— 7
1933	+ 8	— 4	+13	— 1	+10	+15	+ 2	+ 2	+ 8	+17	+14	+15	+ 8
1934	— 8	—33	+ 8	—16	— 7	+ 3	— 2	+ 4	—11	— 1	0	—13	— 7
1935	—10	+14	— 9	+ 1	0	—22	0	— 3	— 6	— 9	+ 6	— 2	— 4
1936	—12	+12	+12	+ 1	— 1	0	— 2	+ 0	+ 4	+15	+ 4	— 6	+ 2
1937	0	—12	+10	0	— 6	— 1	— 5	+ 5	+ 3	— 4	— 8	+28	+ 1
1938	— 6	0	—38	+ 7	+ 7	—11	— 4	+ 7	— 1	— 6	— 4	—12	— 5
1939	—18	—19	+ 3	—24	+ 5	— 9	0	— 2	— 7	+11	— 5	— 4	— 6
1940	+29	+22	+26	+33	+20	+25	+10	+ 5	+ 9	+ 2	+ 7	+15	+17
1941	+11	+18	+25	+19	+30	+ 4	+12	+14	+ 6	+ 8	+12	— 5	+13
1942	+38	+37	— 5	+18	+ 1	— 3	— 4	— 5	— 9	—12	+ 5	— 2	+ 5
1943	— 6	—19	+ 3	—13	—18	0	+ 7	— 9	—12	+ 3	+ 8	+ 3	— 5
1944	—32	— 3	+ 3	—15	—18	— 1	— 8	— 7	— 4	+ 3	+ 5	+ 3	— 6
1945	+22	— 6	—14	— 6	+ 1	0	— 2	+ 8	0	0	+ 3	— 2	0
1946	— 7	—12	0	—14	—14	— 6	—10	— 6	—14	+ 2	+ 4	+ 1	— 7
1947	+26	+20	+ 9	— 9	— 9	— 8	+ 2	+ 6	+ 7	+ 5	— 9	— 3	+ 3
1948	— 3	+ 1	—23	—13	—15	— 4	+ 9	— 3	+ 1	— 5	— 4	+ 4	— 5
1949	— 9	— 3	— 2	—17	— 3	+ 2	+ 3	+ 4	— 9	—11	+ 3	—16	— 5
1950	+ 5	— 3	—10	0	0	+ 2	— 6	+ 0	— 3	0	— 3	+17	0
1951	— 5	+23	+25	+11	+ 6	+ 9	0	+ 4	0	+ 7	— 9	— 3	+ 5
1952	+22	+10	+21	+ 3	+ 7	+ 5	+ 7	+ 3	+14	+ 6	+ 8	+12	+10
1953	— 7	+ 5	— 5	0	+ 5	+ 5	— 3	+ 1	— 3	—	—17	—	— 2
1954	—	—	— 4	+24	+10	+ 7	+11	+ 9	+ 6	— 2	0	—22	+ 3
1955	—21	+ 4	+13	— 6	— 9	0	+ 6	+12	+ 2	+ 3	— 9	— 4	— 1
1956	— 8	+17	— 5	+ 4	—12	0	— 8	— 9	—11	— 7	— 8	— 8	— 5
1957	— 8	—12	—23	—14	+ 1	— 5	— 4	+ 1	+ 1	— 9	0	+ 4	— 6
1958	+11	—13	+21	+25	— 2	+11	+13	+ 8	+ 3	+13	+ 8	+ 6	+ 8
1959	+14	— 5	—12	+ 3	+ 7	+12	+ 5	+ 8	+10	+ 3	+ 3	+ 6	+ 4

TABLE 9. Deviation Δx of the total ozone from the many-year monthly values for Tromsö, 10^{-3} cm (old units)

Year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
1935	—	—	—	—	—	—	+ 3	—19	—14	—35	+ 5	+21	—
1936	—34	—91	— 9	+ 2	—11	— 5	+ 7	— 2	— 5	— 7	—	—	—16
1937	+44	+40	+10	—43	—37	—20	—14	—13	— 7	+ 3	—15	+32	— 3
1938	—	—	—16	+ 7	— 5	— 5	—14	— 1	+ 1	— 5	—	—	— 7
1939	—	—	—36	—31	—13	— 4	— 7	—17	— 7	+10	+33	+15	— 7
1940	+77	+31	+18	+21	+ 2	+14	+23	+22	+10	+ 5	— 6	— 2	+16
1941	+54	+37	+39	+20	+17	+18	+ 3	— 7	+ 1	+13	+15	+49	+26
1942	+41	+50	+56	+11	+17	+ 3	+ 9	+10	+10	+10	— 8	—14	+15
1943	+ 1	+ 3	— 2	— 3	+ 9	— 4	+ 4	+ 8	— 2	— 8	— 7	—45	— 5
1944	—73	—10	—10	—12	— 5	—10	—10	— 3	+ 6	+ 7	0	—36	—15
1945	—39	—15	—13	+12	+ 6	+ 6	— 8	+ 3	+ 7	+ 9	—19	—39	— 9
1946	—60	—20	+ 3	+ 7	— 3	—12	—10	+ 7	— 9	—20	—33	—	—16
1947	—82	— 7	— 5	— 9	0	— 4	+ 3	+ 2	+ 5	+10	—31	—61	—
1948	—19	—33	—28	— 8	+ 1	0	— 1	+ 9	0	— 2	— 3	—	— 9
1949		—44	—35	+ 3	+15	—	—	—	—	—	—	—	—
1957	—	—	—	—	—	—	— 1	+ 8	+ 6	+ 3	+13	+33	
1958	+37	+64	+39	— 9	+ 9	+11	+ 1	— 5	+ 4	+ 5	—37	+48	+20
1959	+49	—10	— 6	+21	+11	+16	+ 5	+ 5	— 3	— 5	+24	—	+13

TABLE 10. Deviation Δx of the total ozone from the many-year monthly values in Zi-ka-wei, 10^{-3} cm (old units)

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1932	—32	—15	— 2	—17	—20	— 6	—6	+ 1	+ 7	+ 5	+ 3	—10	—8
1933	+10	+ 5	— 2	—12	— 6	+13	0	+11	+ 5	— 9	— 2	+ 2	+1
1934	+ 7	—10	+ 4	—17	—13	— 6	+1	— 3	— 5	— 5	—21	—11	—7
1935	+ 9	+17	— 2	— 4	+ 1	— 2	—8	— 4	+ 2	— 2	—10	— 5	—1
1936	+21	+11	+11	+ 3	+ 6	—37	—4	+ 4	+ 4	+ 2	— 4	— 8	+1
1937	—10	— 6	— 6	0	+ 4	0	+2	— 6	— 4	— 3	+ 5	+ 8	0
1938	—	+ 9	+ 2	+14	0	— 1	+1	— 2	—11	— 6	+ 2	+ 6	+1
1939	— 8	—19	— 8	+ 1	— 2	0	+3	— 8	+ 2	+ 3	+ 5	+ 6	—2
1940	+12	+10	+18	+17	+ 4	+21	+3	+10	+ 2	+ 2	+ 4	+ 5	+9
1941	+ 2	— 8	— 6	+ 2	+ 6	+14	+6	+ 3	+ 5	+12	+12	+ 3	+4
1942	— 8	+ 7	— 5	+13	+16	+ 6	+8	— 6	— 3	— 5	+ 9	+ 1	+4

TABLE 11. Rms deviation (σ) and probable error (V) of one-year x-values from the many-year averages, 10^{-3} cm (new units)

Station	Deviation	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Arosa	σ	21.2	22.0	21.1	19.4	14.0	11.1	9.7	9.7	11.7	10.8	9.4	14.8	9.1
	V	14.3	14.8	14.2	13.1	9.45	7.4	6.6	6.8	8.0	7.3	6.3	11.3	6.1
Tromsö	σ	69.9	54.4	33.9	23.5	17.8	14.3	12.4	13.8	9.2	16.2	28.1	49.7	18.9
	V	47.2	36.7	22.8	15.8	12.0	9.7	8.4	9.3	6.2	10.9	18.6	33.5	12.8
Zi-ka-wei	σ	19.4	15.4	10.3	15.2	12.7	19.5	6.3	8.2	7.0	7.8	11.9	8.9	6.2
	V	13.1	10.4	6.9	10.3	8.5	13.1	4.2	5.5	4.7	5.3	8.0	6.1	4.2

2. The observations in Tromsö (North Norway) were begun in July 1935 at the Auroral Observatory. They continue to this day with brief interruptions in some of the winter months. The Tromso Observatory is situated at a latitude where the total ozone amount rapidly fluctuates between very wide limits. For example, on 25 February 1942, $x = 0.585$ cm (the new scale), whereas on 23 and 26 December, $x = 0.068$ cm, one of the lowest figures ever recorded. The winter observations in Tromsö were made on the moon and stars. Cyclonic activity is very strong in the area, particularly in winter; this is apparently one of the reasons for the rapid fluctuations in ozone amount. The Tromsö data which were available to us covered the period from 1935 to 1949 and from 1957 to 1959 (Table 6). They were partly used for comparison with the Arosa figures.

3. The eleven-year series of observations at Zi-ka-wei (near Shanghai) covers the years 1932—1942 /21/. This period is somewhat short for statistical analysis (Table 7).

The observations at Oxford, launched by Dobson in February 1925, were published only for the years 1925—1928 and 1957—1959. They were thus inadequate for our purpose.

Tables 8 through 10 list the deviations of the total ozone amounts in Arosa, Tromsö, and Zi-ka-wei from many-year averages for the corresponding months. From these figures we calculated the rms deviation σ and the probable deviation V of a single monthly average x (derived for one year of observations) (Table 11).

The probable error of a single-year average in Tromsö varies from 0.047 in January to 0.006 cm in September, in Arosa from 0.015 to 0.007 cm, and in Zi-ka-wei from 0.013 to 0.004 in the same months. These accuracy estimates must be taken into consideration when analyzing the IGY data. The probable errors for two years of observations are a factor of $\sqrt{2} = 1.4$ less.

We see from Table 11 that the ozone variability is the strongest in winter, gradually subsiding up to July. Then it slightly increases, again decreases in autumn, hitting the main minimum in September—November. The probable error for monthly values derived over a period of 30 years is as low as 0.001—0.002 cm, but this accuracy is meaningful only for the Arosa observations.

We made use of the Arosa series in order to settle yet another problem concerning the many-year behavior of the ozone amount: we tried to establish the dependence of the maximum and the minimum ozone (daily x-values) on the length (in years) of the observation period. This problem will eventually arise, because the IGY observations covered at most a period of three years, so the corresponding maxima and minima cannot be regarded as many-year values. It is known that the absolute magnitude of the maxima increases as the period of observations is made longer, whereas the minima decrease.

Appendix I lists the maximum and the minimum ozone observed in Arosa during the entire period. Table 12 gives the average maxima and minima calculated for periods of $N = 1, 2, 3, 5, 10, 15$, and 30 years (with the exception of 1926). The averaging was carried out for April, when x_{av} is the largest and the ozone is highly variable, and for November, when x_{av} is at its minimum and the variability is slight. The column for $N = 5$ lists the results for six five-year periods, the column for $N = 10$ the results for three ten-year periods, etc.

Note that there were approximately 21 days every April from which to choose, whereas in November the maxima and the minima each year could be selected from a period of 19 days on the average.

TABLE 12. Average maximum and minimum ozone in Arosa for N years, 10^{-3} cm

Duration N, years		1	2	3	5	10	15	30
April, $x_{av} = 270$	maximum	423	443	455	467	494	502	506
	minimum	315	301	289	279	274	273	258
	amplitude	108	142	166	188	220	229	248
November, $x_{av} = 207$	maximum	319	328	338	344	362	371	381
	minimum	244	238	236	230	224	221	219
	amplitude	75	90	102	114	138	150	162

We see from Table 12 that the amplitude of the daily x-values over a period of 30 years is 75—80% greater than the same amplitude emerging after two years of observation. The leveling out of the minima with the increase in the period of observations is much slower than the peaking of the maxima. These features should be taken into consideration when analyzing the IGY data on maximum and minimum ozone.

DISTRIBUTION OF OZONE IN LATITUDE

Before analyzing the part of ozone in general atmospheric circulation, we have to familiarize ourselves with the mean ozone distribution in the earth's atmosphere. In other words, the synoptic study of ozone should begin with its climatology.

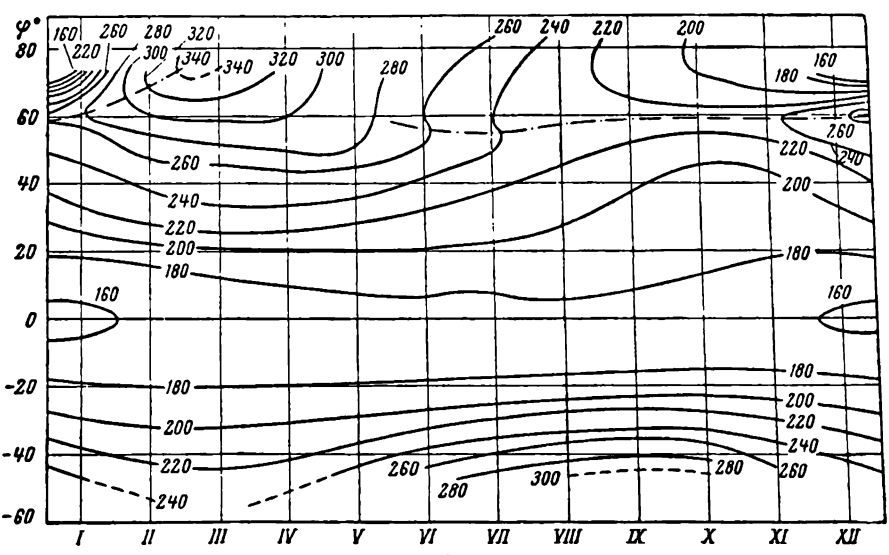

FIGURE 2. Total ozone isopletes after Götz.

The atmospheric ozone is largely dependent on the distribution and the seasonal variation of the solar radiation, which additionally emphasizes the intimate relation between ozone studies and climatology. These "solar" effects, like the temperature field of the atmosphere, are modified by the superposition of horizontal and possibly vertical transfer of ozone by major atmospheric currents. The ozone amount may also depend on local factors. Relatively high ozone was observed, for example, in the descending foehn air /27/. The formation of the ozone layer is inherently similar to the formation of the warm mesosphere layer.

Mean temperature charts preceded the first synoptic maps, and we shall likewise begin with the general or the mean geographic distribution of ozone, and only later focus our attention on rapid ozone variations.

The meridional distribution of the total ozone x during different seasons was studied by Götz /27/ in 1944, by Reed and Julius /46/ in 1951, by Normand /43/ in 1954, by Godson /28/ in 1960, and by others. Their results were presented in the form of isoplete charts plotting the x-values as a function of latitude and time of the year (month). Figure 2 is a reproduction of Götz's original chart drawn in 1944. Götz, however, ignored the dependence of the x-values on longitude, the properties of the underlying surface, etc. The observational material available to Götz and Normand was very limited, and the distribution of the total ozone between different longitudinal sectors could not be examined.

TABLE 13. Monthly zonal x-values, 10^{-3} cm, for 1958—1959

Latitude, N	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
80—90°	376	444	538	460	426	326	319	292	286	318	366	—
70—80	342	458	502	480	458	372	326	304	310	326	358	338
60—70	350	403	428	420	390	360	330	310	287	285	286	298
55—60	362	396	419	416	400	378	354	327	306	298	295	324
50—55	365	395	395	400	376	356	338	317	299	296	310	330
45—50	362	372	398	390	372	362	334	313	295	296	306	337
40—45	335	376	384	376	350	328	302	292	280	282	294	310
35—40	330	346	355	359	358	355	321	308	296	292	291	318
30—35	276	288	308	306	307	310	291	283	272	265	260	274
20—30	242	250	262	270	265	268	257	258	253	250	242	243
10—20	239	244	255	268	274	276	267	267	261	256	242	233
Leopoldville, 4°S	273	269	268	272	270	278	272	277	282	282	276	271

The IGY observations provide data on ozone differences over the oceans and the continents, at least for the northern hemisphere. We shall discuss this point in what follows.

We now consider the latitudinal distribution of ozone ignoring at this stage the dependence of x-values on longitude. Appendix II lists the monthly mean ozone values at all the stations (excluding Naples and Benares, which functioned for a brief period only) for the years 1957—1959. Table 13 gives the monthly mean x-values for latitudinal zones 5° or 10° wide. Neither the monthly averages in Appendix II (calculated from observations over a period

of two and three years, with occasional gaps) nor the zonal means in Table 13 display a "smooth" trend, this irregularity being in general characteristic of climatological data derived from short series of observations. The lack of smoothness is particularly pronounced in the polar zones. Better techniques could of course be suggested for filling the gaps and reducing ultrashort observation series, but we preferred to follow the conventional course because the improved techniques had never been previously applied to ozone.

Figure 3 throws some light on the fit of the IGY data to many-year ozone averages. The two curves in the figure plot the latitudinal distribution of x-values from Götz's diagram /27/ (multiplied by 1.35) and the recent IGY findings.

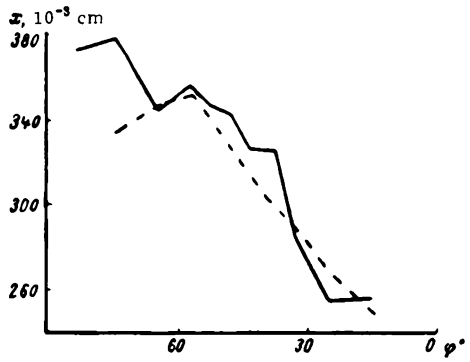

FIGURE 3. Latitudinal distribution of the yearly mean values of ozone according to Götz (broken line) and according to our data for 1958 (solid line).

The fit of the two curves is satisfactory at temperate latitudes (45 — 65°N), but elsewhere the divergence is considerable. However, during the IGY the ozone amount at all latitudes (with the exception of the tropical zone) was higher than in the previous years. For Europe this point will be discussed later.

Northern hemisphere

Figure 4 plots the dependence of x on latitude and season. Figure 5 gives the mean distribution of the total ozone along a meridian for the different months of 1958. The tentative positions of the principal and the secondary ozone maxima, interpolated from Table 13, are shown in Figure 6.

Götz and Normand maintained that the maximum ozone in the northern hemisphere occurs at high latitudes (80°) in the months of February — March only, whereas during the rest of the year it migrates southward approximately to 60°. The substantially more complete IGY data indicate that this

opinion should be thoroughly revised. The concept of a single latitudinal maximum has to be rejected.

We see from Table 13 and Figure 5 that the main maximum appears as early as November—December. In these months the maximum ozone is located in the region of the polar night. The maximum rapidly increases, and literally soars in February. Then it rapidly subsides, decaying by June. In winter the maximum ozone is situated to the north of 80°, and it is only in spring and in the beginning of summer, when the ozone amount is on the decline, that the maximum migrates approximately to 72°. In July—September there is no trace of the main latitudinal maximum in the northern hemisphere.

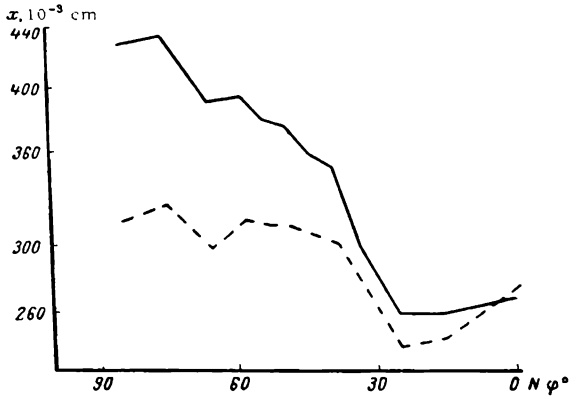

FIGURE 4. Latitudinal distribution of the total ozone in 1958: solid line — January through June; broken line — July through December.

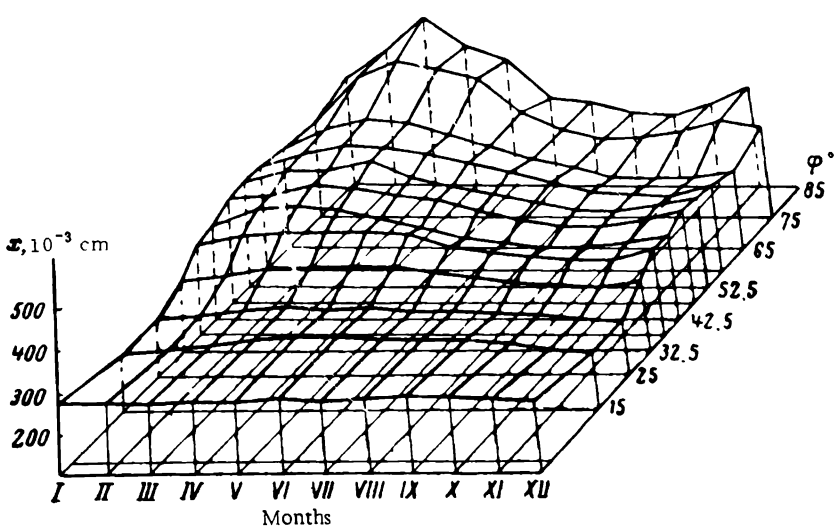

FIGURE 5. Latitudinal distribution of x_{av} for different months according to IGY data.

The monthly average ozone x_{av} in the region of the main maximum in the 70—89° zone is 0.500 cm and higher. The highest springtime values of x_{av} were recorded at Dikson (0.574 cm) in May 1958, Kheis Island (0.545 cm) and Alert (0.530 cm) in March 1958, and SP-6 (0.534 cm) in April 1958. In Tromsö the x_{av}-value during the IGY did not exceed 0.476 cm, although in March 1942 the mean ozone was as high as 0.489 cm. The year 1942 is characterized by a very pronounced positive anomaly of ozone.

The x_{av}-values in the zone of the secondary maximum are substantially lower than in the main maximum. In Aarhus, in March 1958, $x_{av} = 0.482$ cm, and in Moosonee in March 1959 $x_{av} = 0.464$ cm. In summer, the x_{av}-values in this zone do not exceed 0.397 cm (Moscow, July 1958), and in autumn 0.347 cm (Moscow, October 1958).

A third latitudinal maximum is faintly outlined to the scuth of the secondary maximum, but its significance requires further verification.

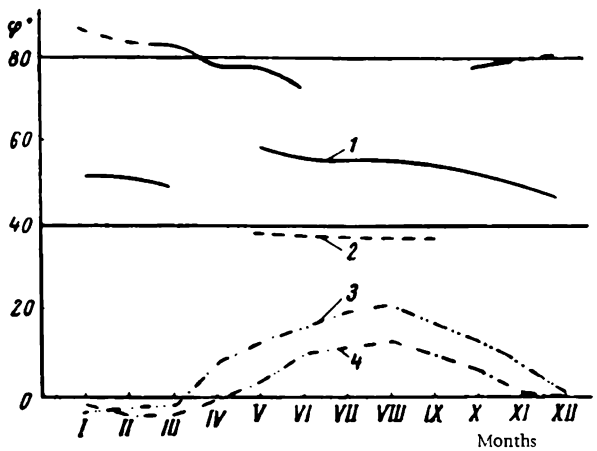

FIGURE 6. Tentative positions:
the curves near $\varphi = 80°$ are the axes of the main ozone maximum;
1, 2) the curves of secondary ozone maximum; 3) the temperature equator; 4) the dynamic equator in the northern hemisphere.

The secondary maximum apparently has an independent existence, and not as a subsidiary of the main maximum. Its seasonal variation is different, and it is more stable than the main maximum during the entire year. However, when the main maximum does appear, the secondary maximum is seen to be much smaller and considerably less pronounced.

In May the secondary maximum is located approximately 58°N. In summer it migrates southward, approximately to 55°; in autumn, winter, and the beginning of spring to 47—48°. The secondary maximum cannot be detected on the basis of the average data only in April. A gap as if forms, and the maximum reappears later, at much higher latitudes.

The x_{av}-value of the secondary maximum gradually decreases in the southerly direction, faster in spring than in summer and autumn. The decrease is particularly steep from 35—40°N to 20—30°N. There is apparently a permanent gap in x_{av}-values over the Eurasian continent, near 30°N. The x_{av} abruptly decreases south of this parallel. We shall show in the following that this gap is even more pronounced in maximum ozone values.

The existence of an ozone gap near 30°N has been previously reported by Ramanathan /47/. The gap roughly coincides with the winter jet stream over Asia. In summer the jet stream passes farther to the north, and it does not explain the gap between the x_{av}-values in, say, Alma-Ata and the Indian stations. This gap is not prominent in the records of oceanic stations in the subtropics, below 30°N (Torishima, Marcus, Maona Loa), where the ozone is considerably higher than in continental subtropical stations of comparable latitude.

Leopoldville (situated slightly south of the equator) again gives x_{av}-values which are somewhat higher than those in the 10—20°N zone. The x_{av}-values continue increasing in the southerly direction. The zone of minimum x_{av}-values is obviously located above the equator, in the northern hemisphere.

The mean position of this zone, which may be called the "ozone equator", is very difficult to determine because of the scarcity of observational data. Some information concerning the position of the "ozone equator" can be obtained by comparing the x_{av}-values for the 10—20°N and the 20—30°N zones. In the period from November to April, x_{av} is typically higher in the 20—30°N zone than in the 10—20°N zone. The minimum ozone in this period apparently occurs below the midpoint of the entire zone (15°N), but not farther off than the equator, since the ozone rapidly increases south of Leopoldville (4°S). From May to October, conversely, x_{av} is higher in the southern than in the northern zone, i.e., the minimum ozone is apparently located between the two midparallels, 15° and 25°N. It is improbable that the minimum occurs at latitudes higher than 25°N, since the x-values increase northward during the entire year. The ozone equator apparently stays in the northern hemisphere all year round.

Table 14 and Figure 6 list the positions of the temperature equator (the line of maximum average zonal temperature) and the dynamic equator (the line of minimum pressure) of the earth. We determined these approximate positions by interpolating the data in the tables appended to the Central Forecasting Institute's "Maps of Many-Year Monthly Averages of Atmospheric Pressure and Air Temperature at Sea Level".* From May to October the temperature equator is north of 13°N, and from November to April it is south of this parallel. Incidentally, this is the reason why the northern hemisphere is on the whole warmer than the southern hemisphere. The dynamic equator migrates in phase with the temperature equator, though with a smaller amplitude.

TABLE 14. Mean global positions of the temperature and the dynamic equators

Equator	Jan.	Feb	March	April	May	June	July	Aug.	Sept	Oct	Nov.	Dec.	Yearly average
Temperature	4°S	3°S	2°S	8°N	13°N	16°N	20°N	22°N	17°N	13°N	8°N	2°N	9°N
Dynamic	2°	4°	3°	0°	4°	10°	12°	13°	10°	6°	2°	0°	4°

* Karty mnogoletnikh srednikh mesyachnykh znachenii atmosfernogo davleniya i temperatury vozdukha na urovne morya.— Moskva, Izdatel'stvo Tsentral'nogo Instituta Prognozov, 1960.

The yearly variation of the ozone equator roughly follows that of the temperature equator. Both migrate in the same direction, nearly in phase; the migration amplitudes are also approximately equal. The amplitude of the dynamic equator, on the other hand, is much smaller. This striking analogy between the ozone and temperature characteristics can be supplemented with another interesting feature. The ozone over the ocean, the tropics included, is somewhat higher than over the continents. This conclusion follows from observations in the northern hemisphere. In the southern hemisphere, where the proportion of water to dry land is much higher, differences of this kind are apparently less pronounced.

Simple geometrical arguments (Figure 7) show that if $\Delta_{oc} = (x_{oc} - x_{cont}) > 0$ and Δ_{oc} decreases in the northern hemisphere toward the equator and then in the general southward direction, the curve $x_{oc}(\varphi)$ should have its minimum considerably farther south than the curve $x_{cont}(\varphi)$. The ozone equator over the oceans apparently extends south of its position over dry land. This property is also displayed by the temperature equator, particularly in summertime.

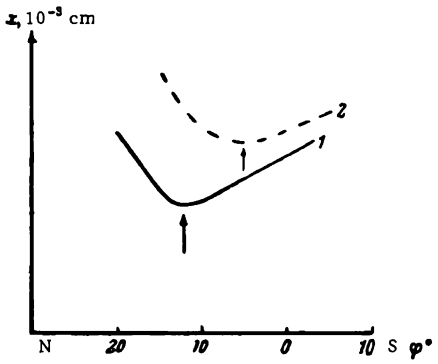

FIGURE 7. Southward displacement of the ozone equator over the ocean:
1) mean ozone distribution; 2) ozone distribution over the ocean.

The ozone and the temperature equator thus have close mean positions, migrate with nearly equal annual amplitudes, and probably display almost identical features of variation over oceans and continents. This implies that the minimum ozone tracks (both in space and in time) the region of maximum temperatures.*

The ozone equator passes mainly in the northern hemisphere, at variance with its presentation in, say, Götz's diagram (see Figure 2). According to Götz, the line of minimum ozone in December—January is at 0° latitude, while during the rest of the year it is located actually south of the equator. Since the ozone equator is in the northern hemisphere, the ozone there should be lower than in the southern hemisphere, at least in the tropics and in the middle latitudes. Kulkarni /36, Figure 5/ published a diagram which plotted the differences in x-values at identical latitudes in the two

* The lowest x-values during the IGY were observed at Tamanrasset in Sahara.

hemispheres up to $\varphi = 55°$ in different seasons. It follows from this diagram that up to $\varphi = 55°$, the ozone in the southern hemisphere is indeed higher than in the northern hemisphere. At 20° latitude, the excess is approximately 0.010 cm, and at 40° latitude, 0.014 cm. The ozone difference reverses its sign only at latitudes higher than 55°.

The above considerations concerning the position of the ozone equator are tentative and mainly qualitative. They are based on the results of very few stations. Fortunately, continental and oceanic stations are equally represented in this sample, which justifies the "averaging" to a certain extent. A more detailed survey of the ozone equator requires several tropical observatories, in the ocean and on the African and South American continents. The ozone equator hypothesis is now generally taken into consideration when planning new investigations and expeditions.

Proceeding from the above data on the position of the ozone maxima (the double maximum in autumn months) and the ozone equator, we constructed a diagram showing the areas (and the periods) in the northern hemisphere with the ozone gradient directed to the equator, and those with the ozone gradient turned poleward. This diagram is highly useful for studying the relation of air currents to ozone variations. If we agree that the "normal" ozone gradient points to the equator, we see that in January—February the "normal" gradient prevails at latitudes from 5 to 75°N. In August, this "normal" zone shrinks to 22—55°N. "Anomalous" gradients (pointing to the pole) prevail to the north of the "normal" zone. They are also observed in the tropical latitudes of the northern hemisphere, the "anomalous" zone growing from 0—5°N in January to 0—22°N in August. The "normal" gradients are the largest in February—May (0.194 cm increment from 70—80 to 30—35°N), markedly decreasing by August—September. The gradient again increases starting in October, when the polar high has reappeared. In autumn (until December), the gradient distribution is more composite, and the relation of air currents to ozone then is apparently the most complicated.

Southern hemisphere

The stations in the southern hemisphere are much fewer, and the observational data are correspondingly poorer, which considerably complicates the analysis.

The autumn maximum at high latitudes is observed in September—October, i.e., substantially later than in the northern hemisphere. The ozone is highest in this period at the fringe of the Antarctica, where the peak x-values were recorded at Mirnyi and Oasis (Bunger Hills). The x-values markedly decrease poleward inside the antarctic circle. The polar depression over Antarctica is much more extensive than in the Arctic. The ozone gradually declines toward the equator; there is possibly an ozone gap at 30°S, the ozone amount dropping abruptly north of this parallel. In summer and in autumn (January—April) the maximum ozone migrates northward, approximately to 54°S; a similar phenomenon is observed also in the northern hemisphere in these months. The polar ozone depression in this period becomes considerably deeper. The total ozone deficit in Antarctica is very substantial in autumn and winter. This constitutes one

of the principal differences between the ozone in the southern and the northern hemispheres. This deficit largely offsets the excess ozone in the tropical and middle latitudes of the southern hemisphere.

The horizontal gradient between 54 and 4°S is the steepest in spring, in October (0.167 cm over 49°), and rapidly diminishes starting in December. At the end of the autumn (April—May), the gradient is half its spring value (0.076—0.078 cm). A secondary short-lived gradient maximum is observed in March, and in places in April, in parallel with the x-maximum in the subtropics and middle latitudes of the southern hemisphere.

Total ozone in the atmosphere

If the mean ozone amounts in the northern hemisphere are known for successive latitude zones 5—10° wide (see Table 13), the mean ozone $\bar{x}_N$ can be calculated for the entire hemisphere. We computed the half-yearly means for the different zones and multiplied each mean by $\sin\varphi_2 - \sin\varphi_1$ (the area of the corresponding zone between the latitudes φ_1 and φ_2). Summing over latitude from $\varphi = 0$ to $\varphi = 90°$, we obtained the $\bar{x}_N$-values for semiannual periods in the years 1957—1959 (Table 15).

TABLE 15. Mean ozone in the northern hemisphere $\bar{x}_N$, cm

Year	Jan.—June	July—Dec.	Yearly average
1957		0.2642	
1958	0.3099	0.2753	0.2926
1959	0.3158	0.2781	0.3029

The average for 1958 and 1959 $\bar{x}_N = 0.2998$ cm

The ozone value for 1958, $\bar{x}_N = 0.2926$ cm, is somewhat less than the value computed by G. P. Gushchin /5/ using 15° zones. In 1959 the ozone amount in the northern hemisphere was 2% higher than in 1958. Note that in the second half of 1957 there was approximately 0.010 cm less ozone than in the corresponding period in 1958—1959.

If we assume that the center of gravity of the ozone layer is on the average at a height of 25 km, the area of the layer at this height over the northern hemisphere is $S = 2.575 \cdot 10^{18}$ cm^2 and the total ozone weighs $1.651 \cdot 10^9$ metric tons. Some 44% of this amount are on the average in the 0—30°N zone and 16% are in the polar zone between 60 and 90°N.

Similar calculations for the southern hemisphere are much more difficult to perform. The stations there were very few, particularly in 1959; some of the stations in 1957 began the observations fairly late, etc. Regular observations fortunately were carried out in the zone between the equator and 42°S, which constitutes nearly 2/3 of the hemisphere. The observations at Halley Bay were also sufficiently systematic.

The stations being few, we could not compute the mean ozone values for successive latitude zones, and we therefore proceeded as follows.

If sufficiently reliable average x-values were available for a certain half-yearly period from stations located at latitudes φ_1, φ_2, ..., φ_i ..., (in order of increasing φ), the i stations were regarded as representative of the zone from $(\varphi_{i-1} + \varphi_i)/2$ to $(\varphi_i + \varphi_{i+1})/2$. The area of this zone is easily seen to be $[\sin(\varphi_{i+1}+\varphi_i)/2] - [\sin(\varphi_{i-1}+\varphi_i)/2]$. This procedure amounts to linear interpolation of the x-value with variable latitude intervals. The northernmost and the southernmost stations which enter these calculations are obviously $\varphi = 0$ and $\varphi = 90°S$. The records of Oasis, Mirnyi, and Dumont d'Urville were combined to represent the 66.5° parallel. The $\bar{x}_S$-values obtained in these calculations are listed in Table 16.

TABLE 16. Mean ozone in the southern hemisphere $\bar{x}_s$, cm

Year	Jan.—June	July—Dec.	Yearly average
1957		0.326	
1958	0.293	0 334	0.309
1959	0.293	0.316	

The year-by-year variation in the southern hemisphere is more pronounced than in the northern hemisphere. This is possibly attributable to insufficient starting data. On the whole, the ozone in the southern hemisphere is somewhat higher than in the northern hemisphere (by 3%). This is consistent with the previous conclusions of Vassy /52/ and the more recent observations of Kulkarni /36/.

The mean ozone amount in the southern hemisphere is $1.705 \cdot 10^9$ metric tons, and the total amount of atmospheric ozone in the two hemispheres is $3.359 \cdot 10^9$ metric tons.

YEARLY VARIATION OF THE TOTAL OZONE

The yearly variation of the total ozone amount is particularly pronounced in the polar region, becoming gradually less distinct toward the equator. In this respect, it is similar to the yearly march of radiation and temperature.

In both the northern and the southern hemispheres the highest monthly x-values are observed in spring. The peak ozone values in the northern hemisphere were 0.574 cm (Dikson Island, May 1958) and 0.545 cm (Kheis Island, March 1958). The monthly means in the southern hemisphere were substantially lower. At Oasis they reached 0.496 cm in September and 0.488 cm in October 1958; at Port-aux-Français (Kerguelen) 0.44 cm and at Macquarie 0.435 cm in October 1958. In the high-latitude stations of the southern hemisphere, such as Halley Bay (75°S) and Little America (78°S), the maximum ozone was considerably lower, not exceeding 0.412 cm (November 1957).*

* The 0.536 cm maximum recorded at Little America in August 1957 was based on no more than two observations on the moon. The observers originally remarked that these data were highly unreliable, since the spectrophotometer was not standardized either before or after the observations in Antarctica

TABLE 17. Time of minimum and maximum ozone (from monthly means)

Latitude	Northern hemisphere: Main minimum τ_3				Main maximum τ_1			Summer rise: Secondary maximum τ_2	Summer rise: Reduced fall of x	Southern hemisphere: Station	Main minimum τ_3			Main maximum τ_1				Secondary maximum τ_2
	1957	1958	1959	Mean	1958	1959	Mean	Mean	Mean		1958	1959	Mean	1957	1958	1959	Mean	1958
80—90°	10.0	(8)	—	9	3	-	3.0	—	—	Leopoldville 4° φ	3	2.5	2.8	—	9.5	—	9.5	4
70—80	8.5	8.0	11	9.2	2	3.0	2.5	—	—	Brisbane 28°	2	2	2.0	9	9	10	9.7	4
60—70	10.7	9.7	9.5	10.0	2.7	3.7	3.2	(9)	6.8	Aspendale 38°	4	1	2.5	9	9	10	9.7	6
55—60	10.4	11.2	10.2	10.6	3.0	4.2	3.6	7.5	6.3	Wellington 41°	3	—	—	9	9	—	9.0	—
50—55	10.0	10.5	9.4	10.0	3.6	3.8	3.7	7.8	7.4	Port-aux-Français 49°	—	—	—	8	—	—	8	—
45—50	10.0	9.5	10.0	9.8	4.0	3.7	3.8	7.0	6.2	Macquarie 54°	2	—	—	10	10	—	10.0	3
40—45	9.7	9.4	9.4	9.5	3.4	3.2	3.3	3.8	7.2	Dumont d'Urville 66°	2	—	—	—	11	—	11	4
35—40	10.1	10.5	11.0	10.5	3.4	5.0	4.2	—	7.0	Oasis—Mirnyi 66°	—	—	—	—	10	—	10	2
30—35	10.0	11.5	10.4	10.5	5.0	4.2	4.6	7.3	7.3	Halley Bay 75°	double minimum			11	11	12	11.7	4
20—30	11.7	11.2	10.7	11.2	4.0	4.0	4.0	8.0	—	Little America 78°	—	—	—	11	—	—	11	—
10—20	12.5	13	(13)	12.7	4.5	6.0	5.2	7.7	(8)									

TABLE 18. Yearly minimum and maximum ozone (from monthly means)

Latitude	Northern hemisphere: Rise time $\tau_1-\tau_3$	Main minimum				Main maximum			Amplitude	Southern hemisphere: Station	Main minimum			Main maximum				Amplitude
		1957	1958	1959	Mean	1958	1959	Mean			1958	1959	Mean	1957	1958	1959	Mean	
80—90°	6.0	235	290	—	263	323	—	323	60	Leopoldville 4° φ	261	272	266	—	282	—	282	14
70—80	5.3	286	300	282	289	484	505	494	205	Brisbane 28°	273	285	279	325	346	318	330	51
60—70	5.2	272	290	275	279	439	433	436	157	Aspendale 38°	280	282	281	365	399	359	374	93
55—60	5.0	282	278	302	287	440	434	437	150	Wellington 41°	261	—	261	349	370	—	360	99
50—55	5.7	278	276	296	283	409	406	408	125	Port-aux-Français 49°	—	—	—	441	—	—	—	—
45—50	6.0	264	292	295	284	399	400	400	116	Dumont d'Urville 66°	311	—	311	442	449	—	446	135
40—45	5.8	262	265	267	265	386	412	399	134	Oasis—Mirnyi 66°	233	—	—	—	311	—	—	—
35—40	5.7	276	287	283	282	380	369	374	92	Halley Bay 75°	—	—	—	393	488	—	—	—
30—35	6.1	270	250	258	259	318	301	310	51	Little America 78°	—	—	—	412	381	354	376	104
20—30	4.8	218	236	242	232	284	288	282	50									
10—20	4.5	232	239	231	234	266	288	278	44									

Table 17 lists the months of the minimum and maximum ozone. In the northern hemisphere the stations were combined in latitude zones, but in the southern hemisphere each station is treated individually (the stations there being very few). The time of the principal spring maximum is designated τ_1, the time of the secondary summer maximum τ_2, and the time of the main autumn minimum τ_3. January is assigned the value $\tau = 1$, February $\tau = 2$, etc.; $\tau = 13$ denotes January in cases when the minimum has shifted from autumn to winter (as in the tropics).

At high latitudes of the northern hemisphere τ_1 is of course established with lower accuracy, since fewer stations are available there, but it is fairly certain that the main maximum occurs in February ($\tau_1 = 2$). It is attributed to the "spring outburst" of ozone, and is therefore high and sharply outlined. At lower latitudes the maximum is observed later, in March and April ($\tau_1 = 3.9$ at 45—50°N). There is a certain recession in the 40—45°N zone ($\tau_1 = 3.2$). This result cannot be discredited as an error: it is analogous to the recession of the main minimum in the 45—50°N zone and is further confirmed by the variation of the time of the absolute extrema. The maximum is progressively delayed farther south, and in the north tropics it is observed as late as May. At Kodaikanal (10°N), for example, this spring maximum coincides with the secondary maximum of the yearly march. The second summer maximum (June—July) is higher in magnitude; it is closer in time to the maximum of the southern hemisphere. Indeed, in these months Kodaikanal is located south of the dynamic and temperature equators, in the circulation pattern of the southern hemisphere, and it may thus be regarded as a station in the "southern ozone hemisphere".

The spring maximum in the northern hemisphere is as low as 0.323 cm near the pole (see Table 18). It sharply increases in the 70—80°N zone, where the spring outburst is apparently the strongest, and reaches a zonal average of 0.494 cm. The maximum gradually declines in the southward direction to 40—45°N, and then drops steeply toward the equator. According to the records of various stations, the maximum ozone diminishes rapidly from 0.400 to 0.300 cm near 35°N. South of this parallel the maxima do not exceed 0.280—0.310 cm.

South of 10°N and farther off into the southern hemisphere, the spring maximum of the northern hemisphere degenerates into a faint secondary maximum of the yearly march. In Leopoldville and Brisbane it is observed in April, in Aspendale in June, but this small peak is very difficult to "pinpoint" with sufficient accuracy against the background of the fairly smooth subtropic ozone curve. There is an attractive hypothesis which explains this secondary maximum in the southern hemisphere by the influx of cold air from the northern hemisphere. In April and May, the cold arctic air advances as far south as the tropics. At least in the northern hemisphere this phenomenon is known to result in a sharp increase of the ozone amount. It is possibly stimulated by the exchange of air masses between the hemispheres.

The weak secondary maximum in March—April was also recorded at high southern latitudes, from Macquarie Islands to Halley Bay, but we are unable to correlate it with processes in the northern hemisphere.

Some authors (Chkhaidze in the USSR /19/, Craig in the USA /21/, and others) report a frequently observed secondary summer maximum in the northern hemisphere. Careful inspection of the tables in Appendix II

shows that this secondary maximum was indeed recorded by 18 stations in the northern hemisphere in summer 1958 and by 12 stations in summer 1959. It is mostly observed in July or August. On the average, $\tau_2 = 7.6$ in the 0—60°N zone. It is much fainter than the main spring maximum. This secondary maximum was most pronounced in 1958 in Voeikovo, Moscow, Potsdam, and Vladivostok; in 1959, though reappearing only in Potsdam and Vladivostok, it was also observed by various stations which had not recorded it in the previous year. In 1957 it was reported by occasional stations. Prior to the IGY, however, it was hardly ever observed in Arosa and Tromsö, though fairly distinct in 5 out of the 11 years of observation at Zi-ka-wei. The summer maximum is thus not only small and unstable, but it is apparently typical of continental stations.

Two alternative explanations of the summer maximum can be advanced:

(1) the increase of tropospheric meridional circulation in summer in the northern hemisphere. This phenomenon, which coincides in time with the maximum ozone, explains the simultaneous appearance of the maximum at all latitudes and its occurrence in the subtropic zone. The main objection, however, is that the enhancement of the meridional circulation in summer may increase the ozone amount only outside the 45—50°N zone (the latitudinal maximum). In Potsdam, for example, a maximum will be observed only under special circumstances, when a zone of high χ-values passes temporarily to the north of the station;

(2) transfer of ozone-rich air from the southern hemisphere, where the ozone amount is on the ascent at that time. It should be noted, however, that the summer maximum generally precedes the main maximum of the southern hemisphere, which is observed not earlier than September—November. Cold antarctic air is as yet unknown to advance along the surface to the equator and farther on into the northern hemisphere. There is a possibility that the influx of warm air in the stratosphere in winter creates warm pockets, e.g., over the Pacific Ocean, which correspondingly modify the circulation. This process has been previously described only for the winter in the northern hemisphere. If it can be shown to occur occasionally in summer also, its relation to the small summer maximum of ozone in the northern hemisphere should be investigated in greater detail.

In the southern hemisphere the main maximum is observed near the equator, at Leopoldville (4°S), in September; as we see from Table 17, it then slowly moves farther south. In October—November, and sometimes as late as December, it reaches the polar region. Its height increases southward, to the antarctic circle. The observations are unfortunately insufficient to maintain with certainty that the ozone amount increases abruptly somewhere between 30 and 40°S, as in the northern hemisphere. Anyhow, in Aspendale (38°S) this maximum is a little higher than at the same latitude in the northern hemisphere, whereas at Macquarie (54°S) it is substantially higher than in the northern hemisphere, which indicates the existence of a large "upward jump" between these latitudes in the southern hemisphere.

South of Macquarie Isl., where the maximum ozone is on the average 0.446 cm, the monthly maxima are considerably less than in the corresponding polar latitudes of the northern hemisphere. The zone of comparatively small χ-values in Antarctica around the South Pole is apparently much more extensive than the analogous zone around the North Pole. It encompasses the entire Antarctic continent; this depression has an extensive

influence, lowering the ozone amount over an enormous area within the antarctic circle. It is remarkable that the comparatively high ozone values at Little America (78°S) were observed at a point where the Ross Sea wedges deep into the continent.

The month-by-month variations of ozone in the southern and the northern hemispheres thus have some features in common, but the differences are very pronounced. The maximum ozone is observed in spring in both hemispheres; the ozone values are smaller in the tropics than at high latitudes. North of a certain latitude, the maximum declines poleward.

In the northern hemisphere, the maximum ozone emerges in the form of a strong outburst at the end of the winter; it propagates southward, arriving on progressively later dates at lower latitudes and gradually decaying. The subtropic surface anticyclones, which occur in summer at 30—35°N, constitute a barrier that nearly damps the maximum ozone, although traces of the maximum are observed also south of the equator.

In the southern hemisphere, the wave of maximum ozone does not display a gradual propagation. We cannot say that the southern ozone is enhanced by outbursts in the polar region, as in the northern hemisphere. Ozone outbursts in the southern hemisphere unfortunately have not been studied yet.

The main minimum is much less pronounced than the main maximum. The time of the minimum τ_3 is also determined with much less certainty. Nevertheless, the dependence of τ_3 on latitude is fairly regular, if we ignore the polar zone where the winter observations are hardly reliable. The minimum occurs in the north polar zone apparently in September ($\tau_3 = 9.0$); it is somewhat delayed at lower latitudes, reaching 55—60°N in $\tau_3 = 10.7$. A slight "recession" is observed farther south, where $\tau_3 = 9.9$ at 45—50°N (approximately one month out of sequence). The delay resumes its progressive growth at lower latitudes: $\tau_3 = 10.8$ at 35—40°N, reaching $\tau_3 = 12.0$ at 10—20°N.

The depth of the ozone depression is much less sensitive to latitude than the height of the maximum ozone (see Table 18). The x-values somewhat increase from the pole to 70—80°N (0.289 cm) and then decline gradually to 35—40°N (0.282 cm). South of 35°N the minimum ozone decreases more rapidly, dropping to 0.232 cm in the tropics. The differences in the minimum ozone values over the entire northern hemisphere, however, are 0.057 cm, whereas the difference in maximum ozone values is 0.216 cm, i.e., four times as large. The minimum ozone is sometimes attributed to photochemical equilibrium processes in the upper part of the ozone layer. Its variation, however, is apparently inconsistent with this hypothesis. The minimum ozone is probably produced by large-scale ascending motions (covering an extensive area), which are particularly vigorous in the tropics and grow weaker toward the pole.

In the southern hemisphere the minimum ozone migrates from Brisbane in February to Halley Bay in May, but its course is difficult to reconstruct because of the scarcity of stations and observations. The minimum x_{av}-values slowly increase to 54°S, and then drop again in Antarctica approximately to the same "depth" as on the equator. Very low monthly ozone values were observed in Tamanrasset ($x = 0.209$ cm in January and July 1958), in Kodaikanal (0.214 cm in November 1957 and 0.217 in December 1958), at Mount Abu (0.219 cm in November 1957), and at El'brus (0.222 cm in September 1958). Most of these records (except

El'brus) are from the tropics, for the cold season. Very low x-values were also observed in the Arctic, at Alert (inside the zone of maximum ozone) in October 1957 and April 1958 (0.235 cm). This figure is remarkable in that it was recorded in a period characterized by an overall upward trend of ozone at lower latitudes. The ozone variation near the pole is thus essentially different from that outside the arctic circle.

Very low mean values of minimum ozone were observed in Antarctica. At Dumont d'Urville, x dropped to 0.233 cm in February and 0.234 cm in May 1958. In this sense, Antarctica is analogous to the north polar region.

We see from the tables in Appendix III that the minima in the tropical zone of the southern hemisphere are never as "deep" as the minima at the same latitudes in the northern hemisphere. The minimum ozone in Leopoldville did not drop below 0.261 cm, and in Brisbane 0.273 cm. This is possibly also attributable to the influence of the ocean, which restrains extreme variations of ozone amount. The restraining influence may be explained by the weaker convection over the ocean than over continental areas in the tropics. General considerations indicate that convection, or ascending currents in general, should lower the ozone amount.

Maximum and minimum ozone

Appendix III lists the maximum and minimum ozone values for the years 1957—1958. The minima and the maxima were selected from among daily mean x-values (we call them "means" for brevity) and individual x-values ("absolute" extrema). Some stations (Tamanrasset, Paris) published only midday x-values; we classified these ozone amounts among the daily means, leaving gaps for the absolute extrema in Appendix III. The mean maxima of stations which carried out uninterrupted daily observations are obviously higher than the maxima of stations which observed intermittently (e.g., only on the direct sun). The absolute maxima of stations with more than one observation a day may be substantially higher than the means. The mean minima should be lower for continuously observing stations, and the absolute minima should be substantially less than the means for stations which recorded several x-values every day. These peculiarities interfere with straightforward comparison of the findings of different stations and obscure the latitudinal and other variations of the maximum and minimum ozone. Two nearby stations may yield different ozone values depending on the frequency of observations.

The latitudinal distribution of the maximum ozone approximately repeats the distribution of the monthly maxima described in the previous section. The highest absolute maximum was observed at Dikson, 0.656 cm on 11 May 1958, at 04.00*. This ozone outburst began on 9 May, when $x = 0.645$ cm at 08.00. Observations carried out before and after the burst maximum reveal an extensive region of very high x-values, and not a sporadic peak (Figure 8). Another exceptionally high ozone value, $x = 0.640$ cm, was observed on Kheis Island at 13.00 on 18 May 1958; between 13.00 and 18.00, the x-values remained higher than 0.565 cm.

* Greenwich Mean Time is used throughout.

The next peak, $x = 0.613$ cm, was registered at Aarhus (Denmark) on 26 February 1958: it is a record value for the middle latitudes; on 24—25 February, $x = 0.577 - 0.561$ cm. At Tromsö, $x = 0.584$ cm was observed on 25 February 1942.

The high ozone $x = 0.607$ cm at Alert on 3 May 1958 suggests that very strong ozone outbursts are also possible in the polar zone, although the mean ozone there is somewhat less than at lower latitudes.

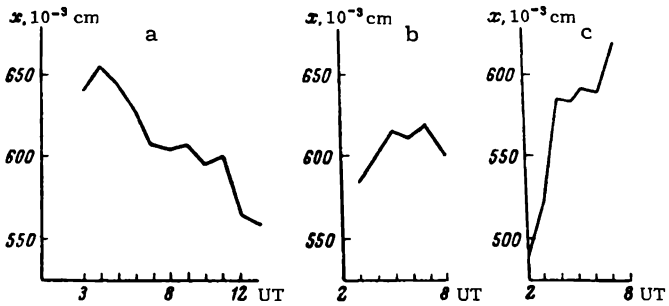

FIGURE 8. Variation of ozone during outbursts on Dikson Island: a) 11 May 1958; b) 22 April 1958; c) 9 May 1958.

In the southern hemisphere, the absolute maxima are substantially lower, e.g., $x = 0.507$ cm on 28 October 1957 at Little America* and a mere 0.439 cm at Halley Bay on 16 November 1957. These figures stress that, even in the period of general rise, the ozone level inside the 75°S parallel is fairly low. Farther from the pole higher maximum ozone is observed. On 28 September 1958, the daily mean at Oasis reached 0.528 cm (the total ozone amount was very high in that period, varying from 0.463 cm on 27 September to 0.512 cm on 2 October). Unfortunately, no hour-by-hour observations were available for Oasis, and the daily means fall short of the Dikson values. A somewhat higher value, $x = 0.533$ cm, was observed at Macquarie in October 1958. The maximum ozone rapidly decreases toward the equator, dropping, say, to 0.258 cm at Kodaikanal.

TABLE 19. Time of minimum and maximum ozone according to daily means and individual observations

Latitude	T_1		T_2				Average for the entire period	
	1958		1957		1958			
	mean	absolute	mean	absolute	mean	absolute	T_1	T_2
60—90°N	2.7	2.7	(11.0)	10.6	10.0	10.0	2.7	10.4
50—60	3.6	3.2	11.1	10.6	11.1	10.9	3.4	11.0
40—50	3.0	3.6	10.3	10.0	10.1	9.6	3.3	10.0
30—40	3.5	3.6	10.4	10.6	11.1	10.2	3.6	10.6
20—30	3.2	3.0	11.6	11.0	10.7	10.7	3.1	11.0
10—20	4.5	3 5	11.0	11.0	12.0	12.0	4.0	11.5
Leopoldville 4°S	3.0	3.0	—	—	12.0	12.0	3.0	12.0

* The ozone value $x = 0.593$ cm observed on the moon at Little America on 10 August 1967 is unreliable

Table 19 lists the time T_1 of the absolute and the mean maxima in 1958. On the whole it is very close to τ_1, the time of the monthly mean maxima. In the 60—90°N zone, $T_1 = 2.7$; at 30—40°N the maximum is delayed, $T_1 = 3.6$, but a slight recession is observed at lower latitudes, where $T_1 = 3.1$. At Leopoldville T_1 again increases to 4.0. The fluctuations in T_1 are apparently less pronounced than the variations in τ_1. The mean absolute maximum, which is equal to 0.590 cm in the 60—90°N zone, gradually decreases to 0.445 cm in the 30—40°N zone and drops rapidly to 0.310 cm at 20—30°N (Table 20). According to some stations, the high maxima terminate abruptly at 30°N. For example, in Quetta (30°N) the absolute maximum is 0.410 mm, whereas in Delhi, located a mere 1.5° farther south, the absolute maximum is 0.325 cm.

TABLE 20. Zonal mean values of maximum and minimum ozone

Latitude	Height of absolute maximum, cm	Depth of absolute minimum, cm
60—90°N	0.590	0.226
50—60	0.518	0.224
40—50	0.473	0.214
30—40	0.445	0.216
20—30	0.310	0.206
10—20	0.281	0.193
Leopoldville 4°S	0.338	0.206

The time T_2 of the minimum ozone was calculated in a similar way from the absolute and the mean minima (Table 19). The minimum occurs in October—November nearly at all latitudes. There is a slight reduction in T_2 at 40—50°, the T_2 then resuming its upward course toward the tropics.

The similarity between the latitudinal distributions of the monthly means and the maximum and minimum ozone (in the sense of this section) implies that the small variations in T and τ that we have observed are indeed significant.

The magnitude of the lowest absolute minima does not change much with latitude: from 0.226 cm in the polar zone to 0.216 cm at 30—40°N. The gap south of this latitude is very indistinct, the minimum ozone decreasing from 0.206 cm at 20—30°N to 0.193 cm at 10—20°N. This is obviously the least variable characteristic of the atmospheric ozone. It also remains fairly constant from month to month.

The lowest of the recorded absolute minima were observed at Tromsö long before the IGY. In particular, $x = 0.091$ cm was registered on 15 December 1940, $x = 0.081$ cm on 28 December 1940, and $x = 0.068$ cm on 23 and 26 December 1942 /50/. At Tromsö the variability of atmospheric ozone is thus extreme: the highest x-values are a factor of 8.7 greater than the lowest values. The variation at Tromsö is also very rapid: on 27 February 1941, only two months after the record minimum of $x = 0.081$ cm, the ozone jumped to $x = 0.570$ cm, the second highest of the recorded maxima.

THE CONTINENTAL EFFECT

By continental effect we mean the difference in ozone amounts over the ocean and the continent, say, along the same parallel. When we have finished with latitudinal factors (i.e., variation of solar radiation and temperature), we shall have to consider the influence of the underlying surface, which is obviously much more complex. This is the first step toward the compilation of ozone charts.

In his address at the International Ozone Conference in October 1959, G. I. Kuznetsov /10/ called our attention to the fact that the meridional ozone gradient along the Dikson—Alma-Ata range according to the 1958 data was considerably higher than at comparable latitudes in Western Europe. This suggested that the continent is deficient in ozone as compared to the coastal areas in the West. At about the same time, Kulkarni, Angregi, and Ramanathan /37/ also published their observations of the continental effect. They showed that in Tateno, near the ocean, the ozone was substantially higher than in Srinagar, inside the Asian continent, particularly in winter and summer of 1957—1958. In 1961 Kuznetsov studied this effect in greater detail /11/, making use of North American observations.

TABLE 21. Continental effect and the influence of jet stream on ozone, 10^{-3} cm

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
10—30°N, I A stations	245	257	266	286	298	300	286	284	275	268	260	248
10—30°N, II A stations	244	246	260	268	256	253	252	251	247	246	240	241
Difference $\Delta A = I A - II A$	1	11	6	18	42	47	34	33	28	22	20	7
Smoothed difference $\overline{\Delta A}$	5	7	10	21	37	42	37	32	28	23	17	9
30—36°N, I B stations	275	294	320	322	329	395	297	289	277	268	253	268
30—36°N, II B stations	277	282	290	288	287	280	266	264	255	252	258	271
Difference $\Delta B = I B - II B$	−2	12	30	34	42	45	31	25	22	16	−5	−3
Smoothed difference $\overline{\Delta B}$	+1	13	26	35	41	41	33	26	21	12	1	−3
Jet stream zone: Sapporo—Kagoshima zone	165	132	128	88	98	55	41	22	32	45	79	114

The simultaneous discovery of the continental effect in the USSR and India was thus one of the IGY contributions. The résumé of the IGY ozone observations enabled the continental effect to be studied in considerable detail. The continental effect was found to behave differently at different latitudes: it is most pronounced in the tropics (10—30°N). We compared the data of two groups of stations which functioned in the 10—30°N zone in the years 1957—1959: I A — oceanic stations on Marcus and Mauna Loa islands; II A — continental stations: Delhi, Mount Abu, Kodaikanal, and Tamanrasset.

Table 21 lists the monthly mean x-values for 1958—1959 for group I A and group II A stations; ΔA in the table is the difference in x-values between the two groups, and $\Delta\overline{A}$ is the smoothed difference,

$$\Delta_i = \frac{(\Delta_{i-1} + 2\Delta_i + \Delta_{i+1})}{4}.$$

The ozone deficit over the continent is very substantial, reaching 0.047 cm according to the unsmoothed data for June. It is highest at the beginning of summer (May—June), declining by wintertime, and reaching a minimum in January. The sea –continent difference thus displays a distinct and fairly smooth seasonal variation, which is approximately parallel to the variation of temperature on the continent. Indeed, in India, the temperature maximum is almost everywhere in May. The difference $\Delta\overline{A}$ increases fairly steeply in spring, particularly in April—May, and gradually subsides at the end of summer and in autumn. This difference cannot be explained by the jet stream over Central Asia: the Himalayan jet stream is at its strongest in winter, when $\Delta\overline{A}$ is small, and vice versa. The continental ozone deficit in this case is therefore not caused by any physical barriers which prevent the influx of ozone-rich air from the north.

In our opinion, the ozone deficiency in this zone is probably attributable to convective motions over the heated continent. In India the mean temperatures in May reach 34—35°. In Timbuktu and Khartoum (Africa), like in India, the maximum temperatures are observed as early as May—June. Vigorous ascending air motions should thus develop in this season over Sahara and over Northwest India. If the general ascending motion in a sufficiently extended area in the tropics also encompasses the ozone layer, the ozone amount should decrease noticeably. This is apparently the main reason for the relatively low ozone in the entire tropical zone.

The summer ozone depression over North Africa and India may be attributed to the northward migration of the temperature and the dynamic equators and of the region of intratropical convergence. In July—August, the advancing sea air or the enhanced meridional circulation apparently level out the sea—ocean difference to a certain extent. In winter, when the temperature equator recedes southward, the ozone amount in the tropics is nearly constant over land and sea.

Let us move farther north, to the 30—36°N zone over Asia and the adjoining part of the Pacific Ocean. Here group I B includes the oceanic stations of Torishima and Kagoshima (Japan), which are entirely exposed to oceanic influences; group II B includes the continental stations of Quetta (Pakistan) and Srinagar (India). The mean yearly variation of the x-values for these two groups and the corresponding ozone differences $\overline{\Delta B}$ are also listed in Table 21. The month-by-month variation of $\overline{\Delta B}$ follows the same trend as $\overline{\Delta A}$, with a maximum in June. The magnitude of the maximum is almost the same as in the 10—30°N zone. Note that in summer the three continental stations used are situated near the Near Asian pressure trough, connected with the advance of the summer monsoon in India and the northwesterly winds from North Iran (the so-called "winds of hundred and twenty days"), i.e., intensive surface convergence of air streams. This is again an excellent example of the sequence "heating→convergence→ ascending motion (and low pressure)→low ozone".

In winter (November to January), the ocean –continent difference in this zone reverses its sign: there is an excess of ozone over the continent. This is probably attributable to the jet stream, which has migrated southward and occasionally admits ozone-rich cold air from the Arctic.

There is plenty of material on the continental effect in the 42—43°N zone. At these latitudes are situated the stations Vigna di Valle near Rome,

Abastumani and El'brus in Caucasus, Alma-Ata at the center of the immense Asian continent, Vladivostok on the coast of the Pacific, and Sapporo at the southern tip of Hokkaido Island. The data of these stations, averaged over three years, are represented in Table 22 and Figure 9.

TABLE 22. Total ozone in the 42—43°N zone, 10^{-3} cm

Station	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct	Nov.	Dec.
Vigna di Valle . .	362	369	388	400	370	356	328	318	311	297	308	336
Abastumani and El'brus	306	373	360	370	320	301	279	277	266	265	260	282
Alma-Ata . . .	283	304	288	281	307	298	284	279	270	264	245	248
Vladivostok . . .	330	345	384	383	362	312	292	280	271	290	297	292
Sapporo	452	443	449	424	413	390	329	308	309	320	339	394

The ozone obviously falls from west to east, in the general direction from Vigna di Valle to Alma-Ata. The ozone deficit over Alma-Ata is particularly large in spring (March—April), over Abastumani and El'brus in summer; this is entirely similar to what we have previously observed for the 10—30°N and 30—36°N zones. The x-value again increases farther east to Vladivostok, although the eastern coast of Eurasia clearly falls short of the ozone values of the western coast. The ozone deficit in Vladivostok, as compared with Vigna di Valle, is particularly pronounced in summer, in July—September, in the epoch of the Manchurian pressure trough. The effect of the Atlantic Ocean (which raises the ozone) apparer extends fairly far to the east, and likewise the effect of the Asian contine which lowers the ozone amount.

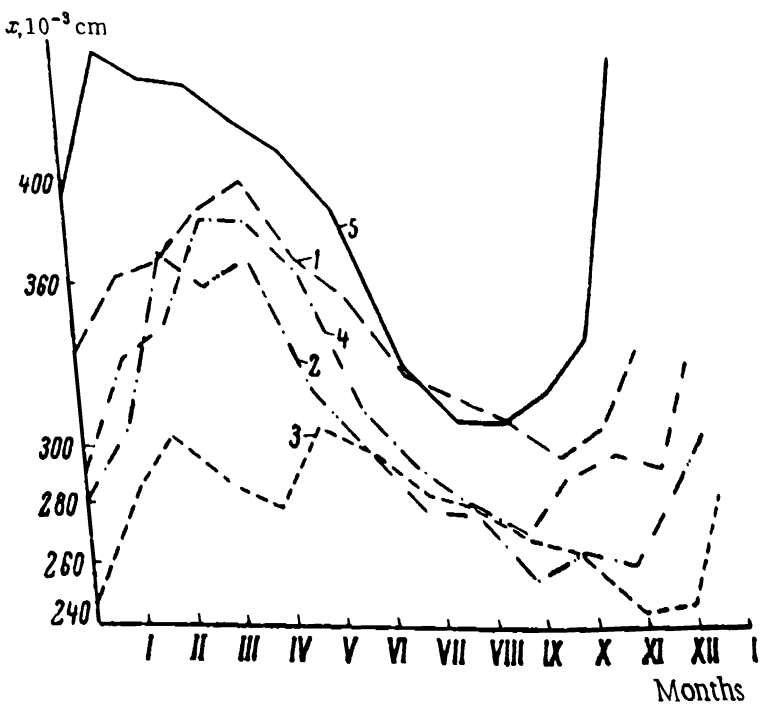

FIGURE 9. Month-by-month variation of ozone

Note that in this time of year westerly winds prevail only in the layer up to 19—20 km. The continental effect is thus manifested mainly in the lower 20-km layer of the stratosphere. Observations show that Cb and Cu cong clouds are extremely thick in this zone, so convection may possibly encompass layers with a high ozone amount. Convection is thus apparently the factor responsible for the variation of ozone.

Figure 9 brings out the very high x-values at Sapporo, where the ozone amount is much higher than for other stations at the same latitude. The Sapporo excess is particularly pronounced in winter, in December—March, sharply declining in summer. Its variation is entirely different from that of the ozone excess in oceanic stations. There are several reasons for this peculiar variation, which can be elucidated by comparing the data of the three Japanese stations, Kagoshima, Tateno, and Sapporo. They are all exposed to oceanic influence approximately to the same degree. Kagoshima (31.6°) is situated on the southern lowland tip of Kyushu Island, Sapporo (43.0°) in a similar locality on Hokkaido Island, and Tateno (36.0°) on the eastern coast of Honshu Island, in a fairly broad and mountainous area.

We see from Table 21 and Figure 10 that the x-values in this group of stations increase all year round from south to north, this increase being more pronounced than elsewhere in the world. The increment Δ_{s-k} (Sapporo-Kagoshima) reaches a maximum in January (0.165 cm). The meridional gradient of x-values in this area reaches its maximum earlier than in other parts of the world, where it is normally peaked in spring. This phenomenon is a reminder of the extreme meridional temperature gradients which are observed in winter.

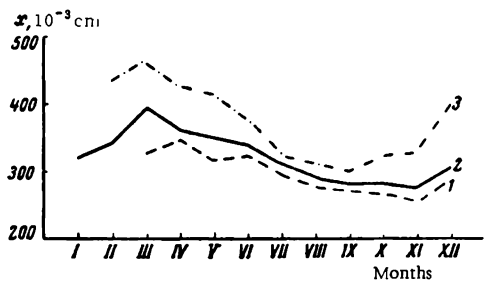

FIGURE 10. Month-by-month variation of ozone in 1958: 1) Kagoshima; 2) Tateno; 3) Sapporo

The steep ozone gradient over Japan is possibly connected with the barrier action of the winter jet stream, whose strength over Japan is unparalleled by jet streams elsewhere in the world. The first aerological measurements in Tateno (in the middle of the "Japanese" section, Figure 10) in 1924—1926 showed that the speed of the southwesterly winds increased enormously in the vertical direction in all seasons, except summer. The wind speed at a height of 10 km was 72 m/sec. This points to a very steep temperature gradient which extends in the northwestern direction throughout the troposphere. For example, on 11 December 1950, at a height $h = 13$ km over Tateno, the wind had the monstrous speed of 116 m/sec. When the jet streams were discovered in 1946—1947, the winter jet over Japan was found to pass at 30°N /41/. It is a confluence of the polar-frontal and the

subtropic jet streams, which explains why the wind speeds are highest in winter; they markedly decline in spring, in April—May.

Back in 1959, G. P. Gushchin /4/ compared the ozonometer readings provided by individual aircraft flights with 1958 synoptic charts and cited several examples of jet streams acting as a barrier against the propagation of ozone from north to south. Very steep ozone gradients thus developed near the jet stream axis. The ozone amounts were high to the north of the stream and low to the south. Gushchin's examples mainly referred to the American—European sector of the northern hemisphere. Since a jet stream frequently develops over a front, these observations can be interpreted as manifestations of the marked difference in ozone between the advancing arctic air and the warmer air of the middle latitudes.

Our analysis of the Japanese IGY observations reveals that the increase in ozone to the north of the jet stream axis is not an episodic phenomenon: it distinctly emerges from the mean data as well. This important persisting feature of the geographical distribution of ozone is confined to a certain season and a certain locality. The increase is particularly pronounced in winter, and becomes less steep in summer. Like the jet stream, it is the result of the high temperature difference between the Siberian continent and the ocean.

Unlike the tropic and the subtropic zones, where the ozone amount is influenced by the summer heating of the continents, the ozone variation in the middle latitudes is mainly caused by the winter cooling of the continental masses. It is for this reason that the variations of ozone are intimately correlated with the winter season.

The Japanese jet stream passes at altitudes of 12—13 km, whereas the ozone advection occurs at altitudes of 16 km and higher. The winter westerlies are even stronger above 16 km. In the warm season they change direction at altitudes above 19 km, where the ozone "barrier" is no longer effective.

The polar jet stream is known to develop mostly over fronts, i.e., approximately parallel to the boundary between cold and warm air. In winter it is hardly possible to distinguish (at least not over the continent) between arctic air proper and the cold polar air of Siberia. The jet stream therefore roughly sketches the southern outline of the area occupied by the ozone-rich arctic air.

In 1876 A.I. Voeikov described intense snow storms which sweep in winter over Hokkaido and the northern part of Honshu; these islands are situated at the eastern fringe of the Siberian barometric high. It is this cold air from Siberia which produces a front, a jet stream, and a boundary between high and low ozone areas.

It should be interesting to reconstruct with greater detail, using the data of ozone stations along the 70—80°E meridian, the effect of the Himalayan winter jet and the Tien Shan summer jet on the ozone distribution over Central Asia, India, and Pakistan.

The analysis of the continental effect in the middle latitudes of the American sector involves considerable difficulties. The following stations are located in the 45—54°N zone in this sector: (1) the highly continental stations of Edmonton (Canada) and Bismarck (USA); (2) the intermediate stations at Moosonee (Canada) on Hudson Bay and Green Bay on Lake Michigan; (3) Caribou near the Atlantic coast. Unfortunately, the Caribou station functioned only during part of the IGY, and the 1959 data are incomplete.

The data of the coastal station in Washington cannot be used because of its southern position.

When analyzing the data for these three groups of stations, we should remember that a fairly strong atmospheric jet stream crosses the North American continent from west to east. For the sake of convenience, we reduced the observations of the five stations to a latitude of 48°N, assuming a gradient of 0.016 cm per 5° of latitude in the 47.5—52.5°N zone and a gradient of 0.030 cm per 5° of latitude in the 42.5—47.5°N zone. The gradients were calculated from global mean values. Table 23 lists the reduced x-values obtained for the five North American stations. The ozone differences are substantially less pronounced than under similar conditions over Eurasia.

TABLE 23. Month-by-month variation of ozone in North American stations of the 44—53° zone reduced to 48°N (10^{-3} cm)

Station	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Edmonton	342	409	426	417	376	348	325	306	293	288	310	328
Bismarck	348	394	408	402	370	343	321	300	289	283	301	331
Green Bay	400	419	405	399	367	349	338	309	298	282	316	354
Moosonee	379	435	427	437	399	376	350	325	312	311	337	369
Caribou	388	404	420	377	383	367	336	—	—	—	—	—

The two continental stations give very close x-values. Moosonee is the most "oceanic" station in this group. The ozone in Moosonee is comparatively high all the year round. The average excess is 0.030 cm relative to Bismarck (rising to 0.039 cm in February). The excess of ozone in the "lacustrine" station of Green Bay is somewhat smaller (some 0.012 cm relative to Bismarck) and highly variable during the year. Here the superposition of the continental effect and the stream jet produces a fairly complex situation.

New ozone stations have recently been set up in the USA and Canada. They will considerably enrich our knowledge of the ozone distribution over the North American continent, of the continental effect, etc. Knowledge of some general features of latitudinal and seasonal ozone distributions over continents and oceans will help us in future in the compilation and analysis of the synoptic ozone charts.

ATMOSPHERIC OZONE AND GENERAL CIRCULATION

Zonal circulation of ozone

The top of the ozone layer at altitudes above 25 km is comparatively constant, and its month-by-month variation is only correlated with the seasonal changes in solar radiation. In the lower part of the layer, below 25 km, where the relaxation time to photochemical equilibrium is long, the ozone is a conservative component of the atmosphere and it is thus transported by air currents over considerable distances. The lower ozone at

any point is thus intimately related to atmospheric circulation and the synoptic conditions: it is as variable as local weather. The extreme ozone fluctuations in the lower stratosphere are conditioned by changes in the total ozone amount over any particular point.

The close correlation between the low-altitude ozone and the total ozone is a long established fact. The total ozone variation is therefore attributed to changes in air currents in the lower stratosphere, in the 10—25 km layer.

Numerous investigations in the last 30 years have dealt with the correlation between the ozone and the temperature at various heights in the lower stratosphere, the tropopause height and temperature, etc. To establish this correlation, one should first elucidate the relation of ozone to different forms of atmospheric circulation. The dependence of ozone on temperature, pressure, etc., may become more or less pronounced according as the general circulation changes.

Back in 1959, making use of the IGY observations, the Moscow State University's Ozone Laboratory compared the ozone amount with the zonal circulation index α calculated for the entire northern hemisphere. This index — the most general characteristic of atmospheric circulation — is defined as the ratio of the mean geostrophic wind to the earth's angular velocity at a certain latitude (generally in the zone between 40° and 65°N), expressed in thousandths. It is routinely computed by the Soviet Weather Bureau for different levels, e.g., 700, 500, 300, 200, 100, and 50 mb. The variations of this index were studied in considerable detail by S. A. Mashkovich and Ya. M. Kheifets /15/.

Figure 11 plots the variation of α for 300, 200, and 100 mb levels (altitudes of about 9, 11, and 16 km) during 1958. We see from Figure 11 that in the upper level α is higher than in other levels in winter (zonal circulation increasing with altitude) and lower in summer (zonal circulation decreasing with altitude).

These diagrams show that the maximum and minimum α at the higher levels (50, 100 mb) come a day or two later than the peaks at the lower levels. Ozone fluctuations also show a certain phase lag relative to circulation at, say, 100 mb.

It has been previously shown by B. L. Dzerdzeevskii and A. S. Monin /8/, Willet /54/, and others that the zonal circulation index varies cyclically. "Long waves" may appear in the period of strong westerly zonal streams in the troposphere and the lower stratosphere, particularly in winter. These "long waves" eventually develop into cyclonic and anticyclonic vortexes which partly absorb the energy of the zonal circulation. The zonal circulation thus subsides, the index α diminishes, and the meridional exchange of air masses is enhanced, leveling out the meridional temperature gradient. Gradually, the cyclones fill and decay, the anticyclones dissipate, and the meridional exchange becomes less intense. The meridional temperature gradients are again increased by the differential influx of solar radiation at northern and southern latitudes, the index α increases, and the zonal circulation is resumed. This concludes the α cycle, which takes five—six days on the average.

We compared the variation of ozone with fluctuations in α at levels of 500, 300, 100, and 50 mb. As expected, the circulation at 100 and 50 mb levels (16 and 22 km) has the largest effect on ozone transport. It is, however, the currents at 500 mb which are the most typical of the general

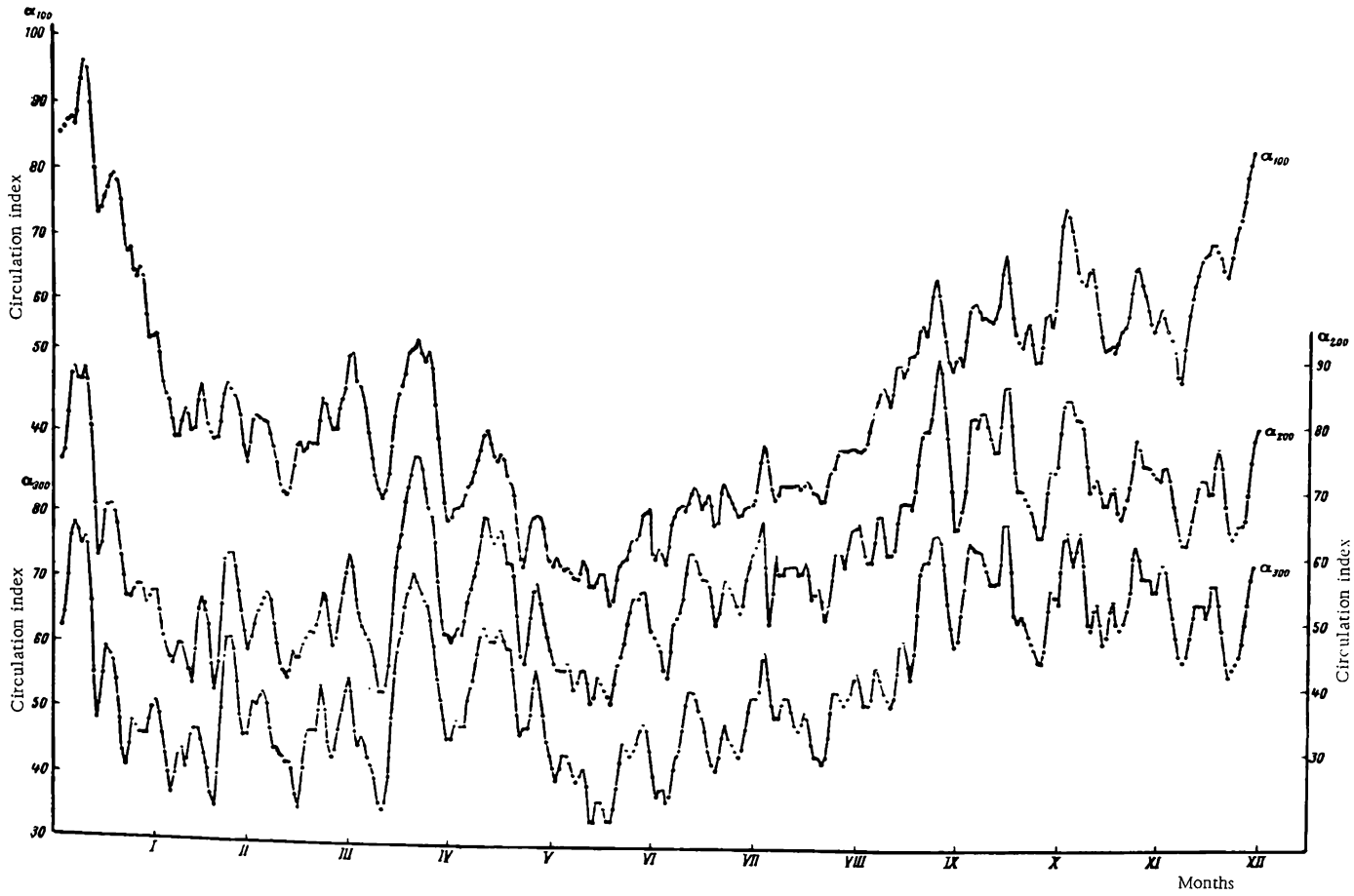

FIGURE 11. Variation of smoothed $\bar{\alpha}$ in 1958 at 100, 200, and 300 mb levels.

atmospheric motions. Charts of this level are commonly used in meteorology and its circulation has been studied most intensively.

The correlation coefficients for the circulation index α and the daily x-values were calculated /10/ for Dikson, Reykjavik, Voeikovo, Uccle, El'brus, Alma-Ata, Vigna di Valle, and Abastumani for different seasons and particularly for January 1958. In 67 out of 97 cases, these coefficients were negative. The positive coefficients are generally small: in 17 out of 29 cases they are equal to 0.16 or less, and have a random character.

The negative correlation between the ozone and the index α indicates that an increase in the zonal circulation reduces the ozone and vice versa. At comparatively low latitudes (El'brus—Abastumani, 42—43°N) this correlation is particularly pronounced in winter, when all $r<0$, because here the ozone gradient normally points south and the x-values are increased by meridional transport (ozone imported from the north). This relation is somewhat obscured at 100—50 mb levels in spring. This is possibly the time of the secondary maximum, which is situated below the main maximum and is connected with advection at comparatively low levels, e.g., 300 mb. In autumn the latitudinal maximum migrates to 45—50°N, and the meridional exchange in the 42—43°N zone has a negligible influence on the ozone amount.

In summer, when the maximum ozone is far to the south from Dikson, Reykjavik, and Voeikovo and the polar peak has dissipated, the meridional transport raises the ozone amount at these stations. This may explain the negative correlation coefficients in the tables in /11/. The correlation in this period, however, is weaker than in winter, since the meridional ozone gradients are sluggish and the random variations of x-values obscure the overall pattern. The gradients and the correlation are even less pronounced in autumn. The negative correlation is strongest at 50 mb, and particularly at 100 mb. At these levels the direction and the character of air transport apparently have the highest influence on ozone variation. In middle latitudes the 100 mb level is probably the most significant.

It should be remembered that the variations of x and α (the two quantities varying in parallel) are large in spring and autumn. This shifts the correlation coefficients in the direction of positive values and complicates the analysis of individual fluctuations.

The relation of the ozone amount to circulation emerges with maximum clarity from a comparison of the day-by-day curves. Figure 12 gives the $\bar{\alpha}$ curves at 100 mb level in the 40—65°N zone, smoothed according to the formula $\bar{\alpha}_i = \frac{\alpha_{i-1} + 2\alpha_i + \alpha_{i+1}}{4}$, and the x curves of Vigna di Valle for 1958.

G. I. Kuznetsov /10/ analyzed the variation of x-values in Vigna di Valle in January—May 1958. The curve of the smoothed index $\bar{\alpha}$ reveals 32 distinct extrema in this period; the curve of x-values has 18 minima and as many maxima. In 15 cases maximum ozone definitely coincides with minimum index, and in 12 cases minimum ozone coincides with maximum index. We see from Figure 12 that these simultaneous extrema are observed in June and even in July. In this period, however, sharp "peaks" of one curve mostly correspond to small serrations of the other.

Beginning in the second half of July, the similarity between the two curves becomes progressively less pronounced. They even display different general trends. In June—July $-\bar{\alpha}$ and x gradually decrease,

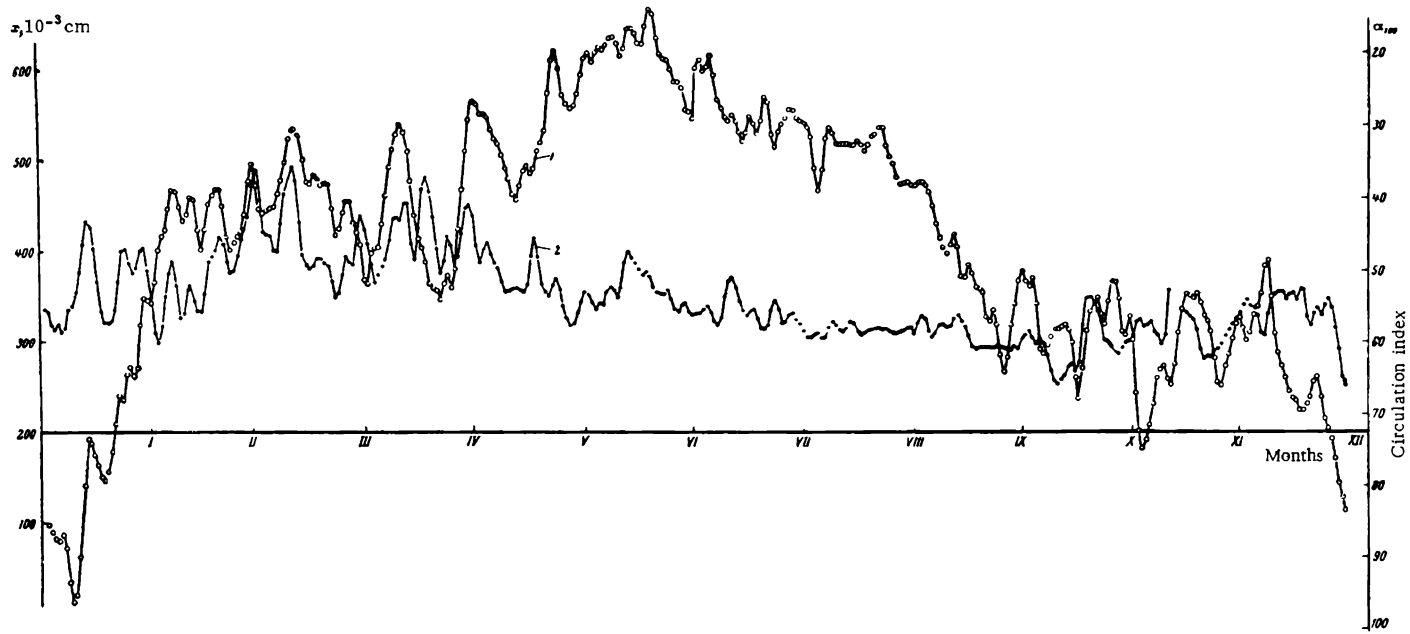

FIGURE 12. Variation of smoothed $\overline{\alpha}$ at 100 mb level (1) and of x-values (2) for Vigna di Valle in 1958. The α scale is inverted

following parallel courses; in August and September, the ozone hardly changed while $-\bar{\alpha}$ continued decreasing. In summer and early autumn the ozone at 42°N thus loses its correlation with zonal circulation.

In mid-October, synchronous extrema recur occasionally (18 October, 30 November, 8 and 21 December), i.e., the correlation between $-\bar{\alpha}$ and x is gradually restored. In the last week of December 1958 there is a particularly sharp fall of ozone and a simultaneous increase of the circulation index. Similar results concerning the correlation between $-\bar{\alpha}$ and x emerge from the Paris curves, but we shall not discuss it here.

The intimate inverse relation between the ozone amount and the index of zonal circulation in winter, spring, and early summer, as well as its absence in the end of summer and in autumn can be explained without difficulty. The sluggish circulation in the 40—65°N zone and the correspondingly enhanced meridional circulation raise the ozone amount in the southern part of this zone, if the maximum x-value occurs in its northern part. This growth of ozone is particularly high when the meridional ozone gradient is steep. In South Europe it is further enhanced by the high-altitude ridge often developing over the Golf Stream (particularly in winter): the northwesterly winds intensify the meridional exchange east of this ridge. Converesely, enhanced zonal circulation as if creates a barrier against atmospheric circulation (a "wind barrier", to use B. P. Mul'tanovskii's term) and prevents ozone influx from the higher latitudes.

If in summer the ozone maximum migrates southward and reaches the latitude of the station, the meridional air exchange loses its effect on the variations of ozone, as we have seen in the data of Vigna di Valle for summer and early autumn. In October—November, however, the polar maximum reappears and the air currents are again able to influence the local x-values.

The dependence of ozone on wind direction, observed by Miyake in Japan /42/ and by Fedele in Italy /24/ is explained in the same way.

In Figure 12 there are marked departures from the linear dependence between $-\bar{\alpha}$ and x in spring. This particularly applies to the period between 28 March and 3 April. At that time, despite the overall increase of α in the entire hemisphere, the local circulation index in the Vigna di Valle area (we denote it by α') diminished. This created an ozone maximum on 30—31 March. The sharp rise in x-values between 14 and 17 May can be analogously explained by the reduction of α' between 14 and 16 May 1958. The third anomaly — the increase in ozone amount on 14—17 April while α' was increasing — is more difficult to explain. The synoptic chart of the hemisphere shows, however, that the circulation was particularly intense south of 40°N; there were only random deviations from the general zonal stream in the areas to the north. The barrier (the subtropic jet stream) passed south of Vigna di Valle in this period.

An entirely different relation of ozone to circulation is observed at the northern stations, e.g., Reykjavik. There is a distinct linear correlation between α and x, particularly at the lower levels, 200 or 300 mb (Figure 13). Enhanced zonal circulation and wind barriers are conducive to ozone buildup, particularly in the period of steep gradients at the end of the winter. This "out-of-phase" fluctuation of x-values in the north and in middle latitudes also emerges from the secular ozone variations in Arosa and Tromsö.

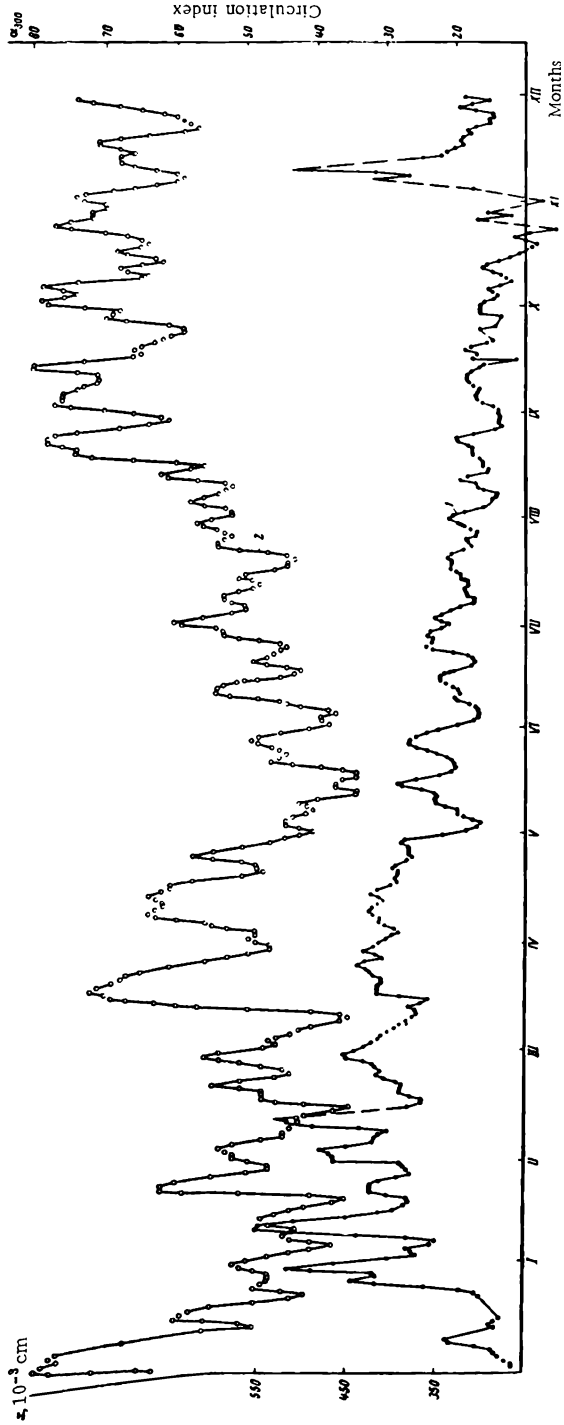

FIGURE 13. Variation of smoothed $\bar{\alpha}$ at the 300 mb level (1) and of χ-values (2) in Reykjavik in 1958

Some features of the variations of x and α point to a more complex chain of cause and effect. Indeed, the ozone maximum produced by the spring outburst is situated far to the north, and even Reykjavik is left south of the high ozone area. Of particular interest is the abrupt growth of x-values in Reykjavik, e.g., at the end of January and in February 1958: the ozone remained low, 0.28—0.30 cm, for a long time, and then rapidly increased from 0.31 cm on 23 January to 0.47 cm on 26 January and 0.54 cm on 30 January 1958. The x-value then slightly dropped to 0.40 cm at the beginning of February, only to jump to $x = 0.57$ on 11 February 1958. This growth was apparently caused by the enhancement of meridional dynamic processes in the lower stratosphere. The index α was gradually falling during that period: between 6 January and 6 February it decreased from 86.9 to 38.8 at the 100 mb level and from 81.5 to 39.4 at the 300 mb level (the fastest fall was recorded between 27 and 28 January).

The increase in x-values in mid-February was apparently connected with enhanced solar activity, bright aurorae, and reduction of the critical F-layer frequencies, as recorded, e.g., in Moscow.

The growth of x-values coincided with a substantial heating of the polar stratosphere. At the station SP-7 (85°N, 157°W), for example, the temperature increased by 21° between 23 January and 1 February 1958 at the 100 mb level, by 38° at the 50 mb level, and by 35° at the 30 mb level. A temperature rise of more than 30° was observed over Canada by Godson /28/.

The relation of the ozone amount to zonal circulation can also be detected in the following way. Let us compare the x-values in Europe in February—March 1958—1959 with those of other months (January, April—December). The yearly mean circulation index at the 100 mb level was nearly the same in 1958 and 1959 (44.6 and 45.0, respectively), but the monthly values for February and March were considerably higher in 1958 (61.1) than in 1959 (41.8). In the other months the relation between the two years was reversed: the year 1958 was somewhat more active, though on the whole the differences in α were small. In February—March 1959, all the stations (except Abastumani, Elmas, and Eskdalemuir) therefore gave substantially lower x-values than in 1958 (see Appendix II), while in the remaining months the 1959 x-values were higher than in 1958 (with the exception of Arosa). This again suggests that the enhanced zonal circulation acts as a barrier. In Reykjavik this effect was fairly indistinct and occasionally reversed its sign. It is not clear why Tromsö, situated at 70°N, behaved like the more southern stations. The main barrier in this part of the northern hemisphere, in the period of particularly high α, probably follows the Golf Stream ("the king of storms", in the jargon of Western sailors) passing south of Iceland but north of the Norwegian coast.

In summing, we should emphasize that the relation between x and α is attributed to two large-scale phenomena — the amount of ozone in the polar "bowl" and its efflux to the lower latitudes. Local irregularities in α play a secondary role.

Meridional circulation of ozone

The previous assumption that a decrease in α implies an increase in meridional circulation is not always self-evident. We therefore examined in greater detail the immediate relation of ozone to meridional circulation, characterized by the Index I_m which had been introduced by A. L. Kats /12/. I_m, like the corresponding zonal pressure gradient Γ_{1-2}, should be calculated for each particular area separately, since these quantities vanish in the mean along any parallel. The IGY synoptic charts of the surfaces from 700 to 50 mb prepared at the Central Forecasting Institute (USSR) provided excellent material for the calculation of I_m and Γ_{1-2}. The interesting results obtained suggested a re-examination of earlier data. The I_m-values and some related characteristics computed by A. L. Kats for a period of years, starting in 1938, were compared with variations of ozone in order to improve our understanding of its secular march.

In /11/ the curve of Γ_{1-2} at the 500 mb level between the Atlantic and South England was examined in conjunction with the curve of x-values for Vigna di Valle. Vigna di Valle was situated approximately downwind from the area for which Γ_{1-2} was calculated. We discovered a considerable superficial likeness between the two curves, both unsmoothed and smoothed by 15-day moving averages. The correlation coefficient between Γ_{1-2} and x was found to be fairly high, +0.55; the correlation coefficient between Γ_{1-2} and the x-value for the next day was even higher, +0.56. The correlation coefficient decreased only when a considerable time lag was allowed: this confirms the suggestion that the ozone fluctuations slowly propagate downstream. We detected a similar correlation in the observations from Bismarck (USA): In April 1958, to give one example, $r = +0.41$. An enhancement of meridional circulation I_m in comparison with zonal circulation I_z raised the ozone amount: in Vigna di Valle, on days with $I_m/I_z > 0.75$, the x-values were approximately 3% higher than on days with $I_m/I_z < 0.75$.

There were several attempts in the past to correlate the ozone variation with the trajectories of the air masses reaching a particular area from the Arctic or from the tropics. The trajectories of air particles in the lower stratosphere, however, are very difficult to construct. Since the trajectories are not computed by weather bureaus, they cannot be applied in routine daily work. We therefore adopted the typical synoptic pattern which had been proposed by A. L. Kats for the Eurasia /12/. Kats's circulation types, which he called western, northern, central, and eastern, characterize the layout of the planetary frontal zones (Figure 14), which slightly shift from winter to summer.

We see from Table 24 that in winter in Vigna di Valle high x-values correspond to circulation types E and C, which import north air to Western Europe, and low x-values correspond to circulation types N and W. In summer the advection reverses its sign and the ozone changes in the opposite direction with each respective circulation type. Over Caucasus, the x-values are raised by N and W processes all year round. The dependence of ozone on the circulation type at El'brus (north of the Caucasus Range) and at Abastumani (south of the Caucasus Range) is approximately the same. This implies that ozone is related to large-scale circulation which is unaffected even by high mountain ranges.

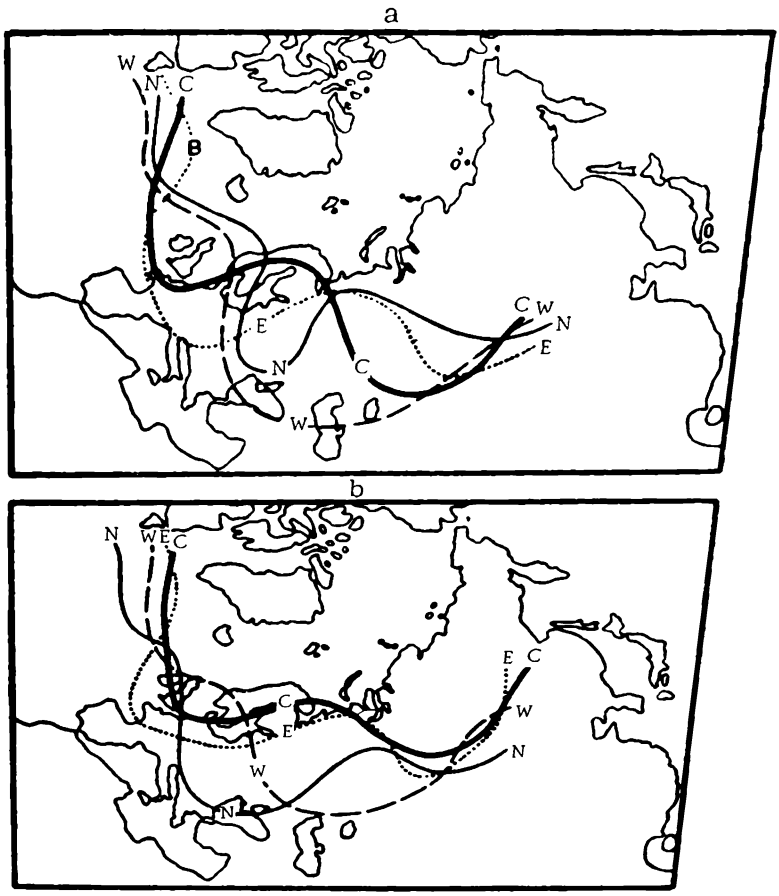

FIGURE 14. Position of planetary frontal zones for different circulation types (according to A. L. Kats):
a — winter months; b — summer months;
W western circulation; N northern; C central; E eastern.

TABLE 24. Monthly ozone amounts in Vigna di Valle according to different circulation types

Circulation types	1957						1958				
	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May
x	326	314	305	292	302	330	360	371	412	419	366
x_N	330	329	305	312	328	324	342	382	400	422	370
x_E	335	310	310	308	327	320	365	—	450	406	356
x_C	320	310	297	285	291	352	395	395	411	433	357
x_W	320	312	—	289	299	322	369	342	390	409	393
x_{CE}	324	310	305	288	304	342	367	395	435	418	357
x_{NW}	334	319	305	297	301	323	352	366	394	419	384

Analogous relations were observed when the Reykjavik data were compared with the pressure gradient along the line from south of Greenland to Jan Mayen to Murmansk. The ozone differences between the CE and NW processes were greatest in winter ($\Delta x = 0.034$ cm) and spring ($\Delta x = 0.023$ cm) and least in summer ($\Delta x = 0.012$ cm) and autumn ($\Delta x = 0.010$ cm). We shall not consider this problem in further detail, as it seems to be pretty clear.

The synoptic ozone relations were studied by comparing the many-year ozone measurements at Arosa with the recurrence frequency of different circulation types. Since the typical synoptic pattern in /12/ had been constructed for the years 1938—1949, we concentrated on the same period in the Arosa observations.

We calculated the correlation coefficients between the mean ozone and the number of days with prevalent meridional circulation ($I_m/I_z > 0.75$). Separate calculations were made for the winter and the summer months. The 1938—1949 data revealed a linear correlation, which was stronger in winter ($r = +0.27$) than in summer ($r = +0.16$). These coefficients cannot be accepted as sufficiently high and reliable, since after all the observations covered a period of 12 years. Much more meaningful results are obtained by comparing the x-values with circulation types.

Below we give the correlation coefficients ($r_{N,x}$) between the x-values and the yearly number of days, N, with different circulation types:

N_C	N_W	N_N	N_E	N_{NW}	N_{NE}
−0.68	+0.10	+0.58	+0.17	+0.52	+0.51

As we see the maximum contribution, though of unlike signs, is from C and N processes. The yearly mean ozone diminishes as the number of days with C circulation increases and grows as the days with N circulation become more numerous. W and E processes are little correlated with the Arosa ozone.

The observed correlation is easily explained. During C processes, Arosa is situated at the western edge of a high-altitude anticyclone, the air streaming from the south. A similar reduction in ozone during surface anticyclones is reported by Dobson and others /9/. Kats has observed that C processes in Western Europe also produce a positive temperature anomaly. During N processes, Arosa is situated on the western periphery of a high-altitude cyclone along which cold arctic air flows to Western Europe and the USSR-in-Europe. The arctic air is high in ozone. It produces negative temperature anomalies in Europe, which are particularly pronounced in winter months. We further calculated the correlation coefficient between x-values and the recurrence of C and N processes in the winter and summer months separately:

	N_N	N_C
November—April	+0.73	−0.45
May—October	+0.56	−0.44

The correlation between ozone and N processes in winter months is clearly much more pronounced than yearly mean correlation.

SECULAR VARIATION OF ATMOSPHERIC OZONE

The observations of three stations — Arosa, Tromsö, and Zi-ka-wei — are adequate for investigating the secular variation of atmospheric ozone. The results of other stations are too intermittent and insufficiently systematic. In Tables 5—7 we listed the monthly x-values for these stations, and in Tables 8—10 the deviations Δx from many-year averages x_{av}. These deviations can be regarded as ozone anomalies characterizing the secular variation of ozone.

Figure 15 plots the variation of the anomalies for the years 1936—1945, smoothed according to the formula

$$\overline{\Delta x_i} = \frac{\Delta x_{i-1} + 2\Delta x_i + \Delta x_{i+1}}{4}.$$

This curve and the numerical data in the tables were used interchangeably, always keeping in mind the difference between smoothed and unsmoothed data. We tried to detect regular, systematic features in the month-by-month variation of the anomalies.

Inspection of Tables 8—10 revealed that during the 30 years of observations in Arosa there were 11 cases of anomalies which persisted for four months or longer (with the exception of the months with $\Delta x = 0$). The persisting negative anomalies were equally numerous. During the 17 years in Tromsö there were 4 persisting anomalies with $\Delta x > 0$ and 8 with $\Delta x < 0$; in Zi-ka-wei there were 4 positive and 3 negative anomalies in 12 years.

The longest persistent anomaly was observed at Arosa in 1940—1942. It was prominent enough to deserve special discussion. The anomaly persisted from January 1940 to November 1941. In December 1941, the Δx-values somewhat decreased, but in January 1942 they rose to the all-time high of +0.038. The growth of Δx occurred in three large waves (see Figure 15) with crests in April 1940, April 1941, and early in 1942, before a steep drop in Δx. On the smoothed curve, all the three waves had approximately the same height, nearly +0.028 cm.

At Tromsö the persistent anomalies in this period were even stronger, rising to +0.077 cm in January 1940. The growth of x-values continued for a longer time than in Arosa: it began in October 1939 and persisted until the end of 1942. The three high ozone waves were also prominent at Tromsö, although the first two appeared a month or two earlier than in Arosa, as if the polar January outburst was very slowly advancing southward. This delay could not be caused by random advances of arctic air: it was definitely attributed to a gradual modification of the atmospheric circulation in the northern hemisphere.

It is especially interesting that persistent anomalies were observed at the same time in Zi-ka-wei, too, though they were less prominent and less regular than in Europe. The first wave emerged at the end of 1939 and was very pronounced: the variation of ozone nearly paralleled that at Arosa. The second (as if split into two components) and the third waves in the Far East came two or three months later than in Europe; they were of smaller amplitude, but their presence is certain.

The positive ozone anomaly in 1939—1942, the strongest during the entire period of recorded observations, apparently encompassed the entire northern hemisphere. This confirms the previous suggestion that Δx is related to atmospheric circulation on a global scale.

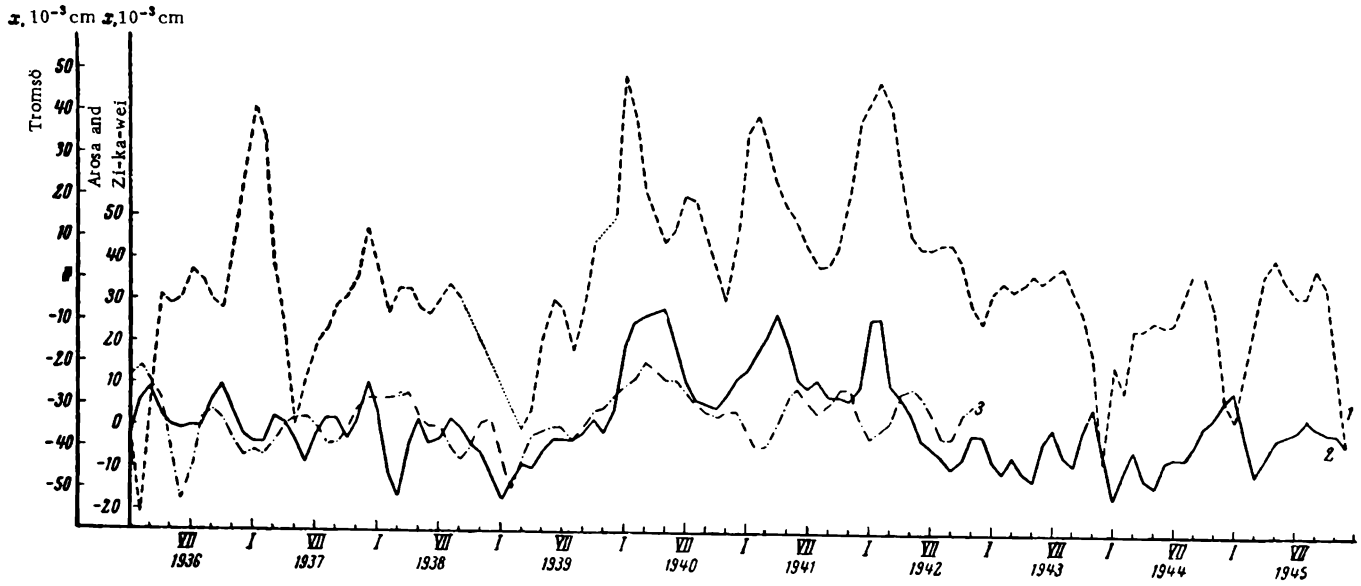

FIGURE 15 Smoothed anomalies of the total ozone amount in 1936 —1945
1) Tromsö; 2) Arosa; 3) Zi-ka-wei

The 1939—1942 ozone anomalies coincided with very strong negative temperature anomalies in Europe. In January 1940, in Berlin, the temperature anomaly ΔT was −8.6°, in February −7.6°, in January 1941 −5.3°, in January 1942 −6.2°. The correlation between these "colder-than-the-average" periods and the "ozone waves" leaves no doubt as to its significance. The correlation is particularly pronounced between the Tromsö ozone and the Berlin temperatures: not only that the ozone anomalies coincide with temperature anomalies, but the first ozone wave has a secondary maximum in July—August 1940. In August 1940 the temperature anomaly in Berlin was −2.7°, which was fairly high for summer.

There was also a brief, but sharp reduction of ozone at Tromsö and Arosa in January 1944. It was apparently connected with the unusually warm weather in January, when the mean temperature anomaly in Berlin reached +5°.

Long persistent anomalies were observed at Arosa (see Table 8) from February to December 1933 and then from November 1950 to January 1953 (with a brief interruption at the end of 1951); they represented high spring outbursts. The positive anomaly of 1954 is more difficult to reconstruct, because the observations are discontinuous. A considerable increase in ozone above the average was observed at Arosa and Tromsö in 1957—1958. On the whole, the IGY ozone values over Western Europe were somewhat elevated. The excess reached some 0.007—0.010 cm in Arosa, and even higher values in Tromsö.

Persistent ozone anomalies with $\Delta x < 0$ were observed at Arosa, with minor interruptions, from November 1931 to January 1933 and then from January 1934 to October 1935. The ozone was low at the end of 1938, the first half of 1939, in 1948, and during almost the entire year in 1956. The curves of Figure 15 show that the ozone depressions are scattered fairly irregularly, whereas the peaks are higher and denser, though of shorter duration.

Comparison of the curves for the three stations reveals yet another remarkable feature. If we exclude the large anomaly of 1939—1942 and that of January 1944, the ozone fluctuations at Tromsö and Arosa are almost never parallel. There is an impression of "counterphase" variation at the two stations, one of which is situated in the polar zone and the other at middle latitudes.

The x-values in Zi-ka-wei and Arosa, on the other hand, often vary in phase, as, e.g., in the middle of 1932, from December 1934 to September 1935, round the year in 1936, in the first months of 1937, etc. If this conclusion is corroborated by the observations of the numerous IGY stations, we shall have definite proof that the total ozone is related to atmospheric circulation in fairly wide latitudinal zones of the northern hemisphere.

The existence of comparatively long anomalous periods suggests that the monthly ozone amounts are not uncorrelated. In other words, the monthly ozone is not an independent random variable and its variation can probably be described by a simple Markov chain. This conclusion is also supported by the fairly high probable error of the yearly mean (see last column in Tables 8—10): it is at least 1.5 times greater than the probable error expected in averaging of 12 independent monthly means.

Table 25 lists the correlation coefficients between the successive monthly x-values for Arosa and Tromsö. Each of the Arosa coefficients was computed from 30—31 pairs of numbers and is comparatively reliable. The systematic month-by-month variation of the coefficients is also proof that the correlation is not a chance phenomenon. During the entire year the correlation coefficient between the Δx-values of any two successive months is positive. In other words, an ozone anomaly, once begun, tends to preserve its sign during the next month.

TABLE 25. Correlation coefficients between successive Δx values in Arosa and Tromsö

Months	Arosa	Tromsö	Months	Arosa	Tromsö
January—February . . .	+0.474	+0.621	July—August	+0.597	+0.608
February—March . . .	+0.232	+0.797	August—September . . .	+0.418	+0.751
March—April	+0.259	+0.371	September—October . .	+0.312	+0.660
April—May	+0.506	+0.679	October—November . . .	+0.305	+0.241
May—June	+0.453	+0.801	November—December . .	+0.126	+0.681
June—July . .	+0.536	+0.671	December—January .	+0.334	+0.605

In Arosa the interdependence between successive months is most pronounced in July—August, declining toward November—December. This winter weakening of correlation is particularly remarkable because it coincides with the period of minimum year-by-year variability of x-values, i.e., random errors and small fluctuations apparently obscure the large "ozone waves". The ozone waves are probably smaller or less prominent in the second half of the year.

The correlation coefficients for Tromsö are invariably higher than those of Arosa, but the Tromsö series being the shorter of the two, these results are less reliable. We therefore do not analyze their peculiar features.

The general growth of the Arosa coefficients which begins in December is interrupted by a sharp fall in February—April. If the corresponding figures are indeed significant, we are dealing here with a remarkable property of atmospheric ozone: at the end of winter, brief but very intense fluctuations of the ozone amount are superimposed on the regular variation of x-values, distorting and often breaking the large "ozone waves". These short-lived processes apparently include the spring ozone outbursts repeatedly described in the literature.

We did not analyze the correlations in x-values removed by two and more months. This possibility, however, should not be neglected, since only the large anomalies of atmospheric circulation may explain the existence of long ozone waves.

The IGY observations, carried out for the first time according to a common schedule and on a very large scale, provided remarkable experimental results. There is now a previously unparalleled volume of information on the latitudinal distribution of ozone, including the main and the secondary latitudinal minima. The existence of an ozone equator was established, and the ozone in the southern hemisphere was found to be consistently higher than in the northern hemisphere. The month-by-month variation of ozone was studied; the second summer maximum, in particular,

was seen to be highly unstable. Continental and oceanic effects were described, and the jet streams were proved to influence the ozone distribution in a certain way, these factors varying from season to season. There is now sufficient material available for the compilation of synoptic ozone charts.

The relation of ozone to the general atmospheric circulation, and particularly to the zonal circulation in middle latitudes and to local meridional air exchange was demonstrated to be of considerable significance. The action of these factors is manifested in the day-by-day variation of ozone, as well as in its dependence on large-scale synoptic patterns and many-year fluctuations. Some of the effects, e.g., the influence of arctic air and cold winters on the ozone amount, can be interpreted without difficulty. Other phenomena, e.g., the origin of the winter—spring maximum and the ozone "outbursts", which are apparently attributed to the circulation of ozone in the upper layers and its settling in the arctic anticyclones, require further theoretical and experimental research.

The experimental material obtained is probably adequate for synoptic studies of general circulation, as well as for the development and verification of a more complete and detailed theory of atmospheric ozone, which will take into account its transport by large-scale air currents.

Chapter Two

OZONE OBSERVATIONS IN MOUNTAINS AND THE AEROSOL COMPONENT OF SCATTERING

Atmospheric ozone observations at the mountain station of El'brus were carried out by a Moscow State University expedition between 9 and 20 August 1962. The total ozone was measured with a spectrophotometer designed at the Main Geophysical Observatory (USSR). The observations were carried out at different altitudes: on 9—10 August at Terskol (2150 m), on 12—18 and 20 August 1962 at "Priyut odinnadtsati"* (4050 m), and on 19 August at the El'brus saddle (5300 m above sea level). The ozone amount was determined on the direct solar spectrum at 3100 and 3700 Å, making use of the nomograms constructed for the appropriate heights /6/.

Table 26 lists the daily mean x-values for the entire period of observations (the number of observations on each particular day is given in parentheses). The tropopause height h_{tr} and the temperature T at 500, 300, and 100 mb levels are also given. The values of h_{tr}, T_{500}, and T_{100} were borrowed from the bulletins of the Central Weather Institute.

TABLE 26. Results of El'brus observations

Date, Aug. 1962	Altitude, m	x, 10^{-3} cm	h_{tr}, km	T°_{500}	T°_{300}	T°_{100}
9	2150	266 (19)	12.3	—10	—36	—64
10	2150	267 (30)	11.0	—11	—35	—65
11	4050		11.0	—10	—33	—65
12	4050	251 (35)	12.7	— 9	—28	—67
13	4050	254 (48)	11.8	— 8	—32	—66
14	4050	265 (13)	11.8	— 9	—31	—61
15	4050		9.2	— 9	—34	—
16	4050	267 (30)	10.6	—10	—34	—62
17	4050		11.8	— 9	—35	—66
18	4050	256 (39)		—11	—32	—60
19	5300	251 (18)		— 9	—31	—
19	4050	252 (6)		— 9	—31	—
20	4050	259 (22)		—10	—34	—60

We see from Table 26 that there is a distinct negative correlation between x and h_{tr} and between x and T_{300}. The negative correlation between x and T_{500} and the positive correlation between x and T_{100} are less pronounced.

* [Literally, "Shelter of the Eleven".]

The pattern emerges from Figure 16, which plots the variation of x, h_{tr}, T_{500} and T_{100} in the period from 9 to 20 August 1962. Table 27 gives the correlation coefficient r between the ozone amount x and h_{tr}, T_{500}, T_{300}, T_{100}. These coefficients are fairly reliable, despite the shortness of the observation period.

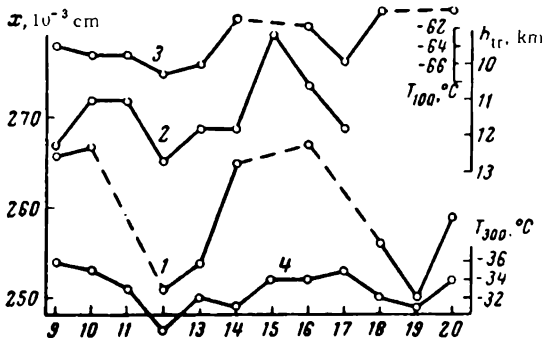

FIGURE 16. Variation of the ozone amount x (1), the tropopause height h_{tr} (2), the temperature at the 100 mb level T_{100} (3), and the temperature at the 300 mb level T_{100} (4) between 9 and 20 August 1962.

TABLE 27. Ozone correlation coefficients

	x, h_{tr}	x, T°_{500}	x, T°_{300}	x, T°_{100}
r	—0.64	—0.47	—0.73	+0.30

The correlation clearly reverses its sign in the interval between 9 and 16 km, from negative in the lower levels to positive at the higher altitudes.

Inspection of barometric pressure charts showed that a high-altitude trough extended over Caucasus on 8—9 August, which was very pronounced at the 300 and 100 mb levels. Northerly and northeasterly winds prevailed over Caucasus. When a high-altitude ridge reached the observation area on 11—13 August, the prevalent winds gradually changed to southerly. On 12 August, however, a powerful high-altitude cyclone formed over the Lower Volga area, and Scandinavian and Baltic air flowing along its western periphery started reaching Caucasus. The ozone therefore markedly increased on 13—14 August, when a cold front passed over El'brus. From 16 to 20 August the observation area was influenced by high-altitude anticyclones situated approximately over Iran. Southern air masses originating possibly as far south as Sahara advanced to Caucasus. The lower tropopause gradually dissipated, disappearing entirely on 18 August. The ozone correspondingly decreased with the advance of tropic air.

A latitudinal ozone gradient was thus observed over El'brus as early as August, and the horizontal motion of air masses in the lower stratosphere caused the usual variations of the ozone amount. Influx of northern air raised the x-values, whereas southern air lowered the ozone. The fluctuations of x-values in that period could also be caused by vertical motions through a substantial portion of the lower stratosphere. It is probably these motions that are responsible for the positive correlation between x and T_{100} and the negative correlation between x and h_{tr}.

The observations at the Shelter of the Eleven apparently corroborate the existence of a previously reported /19/ slight growth of ozone between 09^h00^m and 16^h00^m. On the brightest days — 13 and 18 August — the mean x-value changed from $09^h00^m - 10^h00^m$ to $15^h00^m - 16^h00^m$ as shown in Table 28. A similar growth was also observed on 19 August at the El'brus saddle, where the ozone increased from 0.248cm before midday to 0.253 cm past midday. On the whole, the hour-by-hour variation of ozone was indistinct.

TABLE 28. Daily ozone variations

Date, Aug. 1962	Average x-value for $09^h00^m - 10^h00^m$, cm	Average x-value for $15^h00^m - 16^h00^m$, cm
13	0.255	0.258
18	0.260	0.261

One of the principal tasks of the expedition was to evaluate, from measurements at different altitudes, the effect of aerosols on the measured ozone amount. The aerosol component of scattering is known to decrease fairly rapidly with altitude in the troposphere. At each particular height it can be expressed as a sum of two terms:

$$\delta_\lambda = \delta_\lambda(h) + \delta'_\lambda(h, t), \qquad (1)$$

i.e., a constant term, which remains time-independent for a few consecutive days, and a variable term. The first term may be attributed to the existence of a uniform static layer of turbidity in the atmosphere. The second term is contributed by moving dust clouds, water or ice particles, fragments of clouds, etc. It is the main source of the rapid fluctuations of the solar radiation measured in different spectral regions by the ozone instrument. Some authors erroneously attribute these fluctuations to changes in the ozone amount.

If we neglect the variations of the ozone layer, which are generally very slow, and the instrumental errors, we can write a single-valued expression relating the variations of the ozone amount x to the fluctuations of the variable aerosol component at any given height:

$$\Delta x \sim \frac{1}{\alpha_\lambda}\Delta\delta'_\lambda \quad [\text{or} \quad \Delta x \sim \frac{1}{\alpha_{\lambda_1} - \alpha_{\lambda_2}}\Delta(\delta'_{\lambda_1} - \delta'_{\lambda_2})], \qquad (2)$$

where α_λ is the ozone absorption coefficient in cm^{-1}.

The variance of the observed ozone amount at the altitude h was described by the standard deviation $\sigma_x(h)$ of the ozone amount during a certain period:

$$\sigma_x(h) = \sqrt{\frac{\pi}{2}} \frac{\sum_{i=1}^{n} |\Delta x_i(h)|}{n - 1/2}, \qquad (3)$$

where Δx_i are the individual deviations in x_i. Introducing a certain mean deviation $\overline{\Delta x(h)}$ and making use of (2), we rewrite (3) in the form

$$\sigma_x(h) = \sqrt{\frac{\pi}{2}} \frac{n}{n - 1/2} \overline{|\Delta x(h)|} \approx \frac{1}{\alpha_{\lambda_1} - \alpha_{\lambda_2}} \Delta \overline{[\delta'_{\lambda_1}(h) - \delta'_{\lambda_2}(h)]}. \qquad (4)$$

The standard deviation $\sigma_x(h)$ was determined from observations between 10^h30^m and 12^h30^m on the brightest clear days. These two hours are the least cloudy and are in general favorable for ozone measurements. The $\sigma_x(h)$ calculated for this period are listed in Table 29.

TABLE 29. Standard deviation of ozone amount

Date, Aug. 1962	Height, m	Number of observations	$\sigma(h)$, cm	$\sigma(h) = \frac{K}{\alpha_{\lambda_1} - \alpha_{\lambda_2}} \Delta \overline{[\delta'_{\lambda_1}(h) - \delta'_{\lambda_2}(h)]}$
9		19	0.010	
10	2150	13	0.012	0.011
12		15	0.008	
13	4050	12	0.007	0.007
16		10	0.007	
18		15	0.005	
19	5300	15	0.003	0.003

We thus established the vertical trend of the variable aerosol component, apart from a constant term

$$\frac{K}{\alpha_{\lambda_1} - \alpha_{\lambda_2}} = \sqrt{\frac{\pi}{2}} \frac{n}{n - 1/2} \frac{1}{\alpha_{\lambda_1} - \alpha_{\lambda_2}}$$

The change $\Delta \overline{[\delta'_{\lambda_1}(h) - \delta'_{\lambda_2}(h)]}$ with altitude is plotted in Figure 17. The variation of the standard deviation with height is approximately represented by the straight line

$$\sigma_x(h) = \frac{K}{\alpha_{\lambda_1} - \alpha_{\lambda_2}} \Delta \overline{[\delta'_{\lambda_1}(h) - \delta'_{\lambda_2}(h)]} = [0.017 - 0.0026h] \text{ cm}, \qquad (5)$$

where h is the altitude of the observation site above sea level, in km.

It is remarkable that from equation (5) we have $\delta(6.5\,\text{km}) = 0$, i.e., the ozone fluctuations attributed to rapid variations of the aerosol component

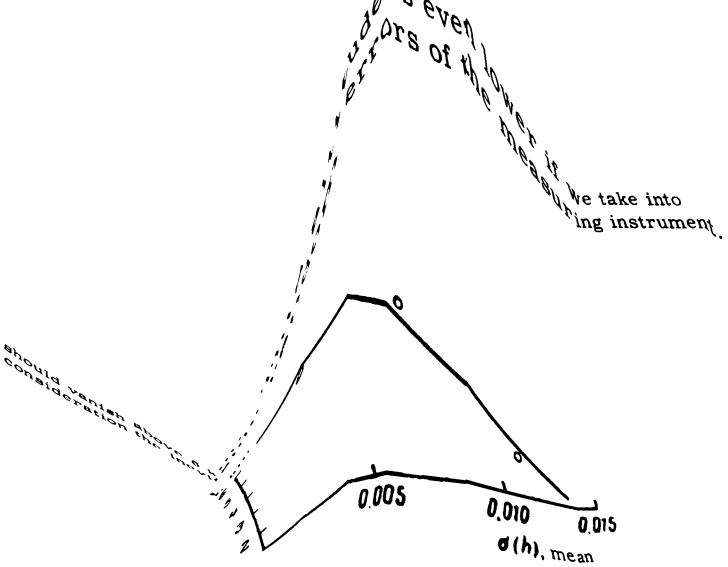

FIGURE 17. Variance of the variable aerosol component as a function of the altitude of the observation site.

Further ozone measurements at high altitudes, and particularly simultaneous observations at different levels will help to elucidate the role of the aerosol component of scattering in ozonometry.

Chapter Three

VARIATIONS OF OZONE CAUSED BY VERTICAL MOTIONS IN THE ATMOSPHERE

Back in 1950—1951 Reed and Julius /46/ studied the influence of vertical air motion and atmospheric turbulence on the vertical ozone distribution and the total ozone. They came to the conclusion that neither of the two mechanisms could cause substantial fluctuations in x-values.

Later Paetzold /45/ advanced a new hypothesis, according to which the top of the ozone layer destroyed by descending motions which transport ozone in the downward direction is regenerated by photochemical processes, which are sufficiently fast at these altitudes. In the lower part of the layer, on the other hand, the ozone builds up, because the photochemical processes are very slow there and the ozone amount decreases at an insignificant rate approaching the equilibrium photochemical concentration of the low levels. The total ozone in a layer with descending motions will consequently increase. The ozone amount analogously decreases in the presence of ascending air motion. Paetzold's conclusions partly contradict Reed and Julius /46/. As far as we know, Paetzold did not perform any calculations. His expression for the vertical ozone transport /45/ was not used as a basis for any analytical or numerical treatment. And yet, Paetzold's hypothesis have become very popular with various authors who apply it to explain different features in the behavior of the ozone layer.

Since 1959 G. P. Gushchin /4/ has been working on a somewhat different idea, specifically that the ozone is transported downward by turbulence. He has developed an approximate theory of yearly and other variations of the ozone amount at two levels.

We shall try to describe the changes in the vertical ozone distribution and in the total ozone caused by ordered vertical motions (either upward or downward), taking into consideration the contribution of photochemical reactions to ozone production and decay. The mean vertical ozone distribution which emerges from the experimental data is adopted as the equilibrium distribution in the absence of vertical motions. The photochemical relaxation time is assumed to be independent of circulation.

If photochemical processes were the only factor affecting the ozone, we could write

$$\frac{d[O_3]}{dt} = z'[O][O_2][M] - K[O][O_3] - I'\varphi', \qquad (1)$$

where [O], [O_2], [O_3], and [M] are the concentrations of atomic oxygen, molecular oxygen, ozone, and "third-party" particles which participate in ozone-producing triple collisions; I' is the quantity of ozone-dissociating

ultraviolet energy absorbed by the ozone molecules; φ' the yield constant of the photochemical ozone-breaking reaction; z' a rate constant of ozone production (in cm^6/sec); K the rate constant of ozone decomposition in collisions with oxygen atoms (in cm^3/sec).

In equilibrium,

$$[O_3] = \frac{z'[O_2][M]}{K} \cdot \frac{I\varphi}{I'\varphi' + I\varphi}, \qquad (2)$$

where I is the absorption of the oxygen-dissociating energy; φ the yield constant of the oxygen-dissociation reaction. If the equilibrium has not been attained, we may write

$$\frac{d\rho}{dt} = \alpha(\rho_0 - \rho), \qquad (3)$$

where ρ_0 and ρ are the equilibrium and the actual (partial) density of ozone; α is the relaxation coefficient, equal to the reciprocal of the time τ to equilibrium photochemical-ozone concentration:

$$\tau = \frac{z'[O_2][M]}{K(I\varphi + I'\varphi')}. \qquad (4)$$

The factors I and I' entering the above equations require detailed knowledge of the energy distribution in the ultraviolet spectrum at wavelengths which induce ozone dissociation, as well as at wavelengths dissociating oxygen molecules and thus providing "raw material" for ozone formation. I and I' are required at all levels of the ozone layer, corrected for extinction (absorption and scattering) in the upperlying strata. The intensity I_0 of the solar radiation at the upper boundary of the atmosphere is available from rocket-sounding data /2/:

λ, Å	I_0, erg·cm^{-2}·sec^{-1}	$\alpha_{O_3}^*$, cm^{-1}	α_R^*, 10^{-6}cm^{-1}
2400	1.612	205.8	4.4
2600	4.55	259.0	3.22
2800	8.40	101.3	2.3
3000	20.7	9.3	1.68

In calculations we make use of the atmospheric absorption equation

$$I_{atm} = I_0 e^{-\alpha_{O_2} m_1 - \alpha_s m_2 - \alpha_{O_3} \mu x}$$

(where m_1, m_2, μ are the optical masses of oxygen, the atmosphere, and ozone; x is the ozone amount). Putting $\mu = m_1 = m_2 = 1$ (zenith sun), we write

$$I' = \alpha_{O_2} I_{atm}; \quad I = \alpha_{O_3} I_{atm}.$$

I was calculated to first approximation from the ozone distribution observed over Arosa on 25 July 1958, when the total ozone was low (x = 0.245 cm), and from the mean distribution observed between 18 July

* α_{O_3} is the ozone absorption coefficient /53/; α_R the Rayleigh scattering coefficient /48/.

and 11 August 1958, when $x = 0.305$ cm. The last figure is approximately the worldwide average x-value (see Figure 4, broken curve).

The ratio z'/K in (2) is a function of temperature:

T, °K	223	273	323	373
z'/K, cm^3	$4.05 \cdot 10^{-19}$	$3.44 \cdot 10^{-20}$	$6.40 \cdot 10^{-21}$	$1.85 \cdot 10^{-21}$

The temperature distribution used in calculations was that corresponding to the new standard model atmosphere of the USSR.

The relaxation time τ was thus obtained for different heights. For the lower x-value, it was 70 sec at the 48—50 km level, rapidly increasing to 10^5 sec, i.e., nearly a whole day, at 26—28 km. Even greater τ were obtained at lower altitudes. For the higher x-value, τ is somewhat larger, nearly 100 sec, at the 48—50 km level; between 30 and 42 km τ is somewhat less than for the lower x-value.

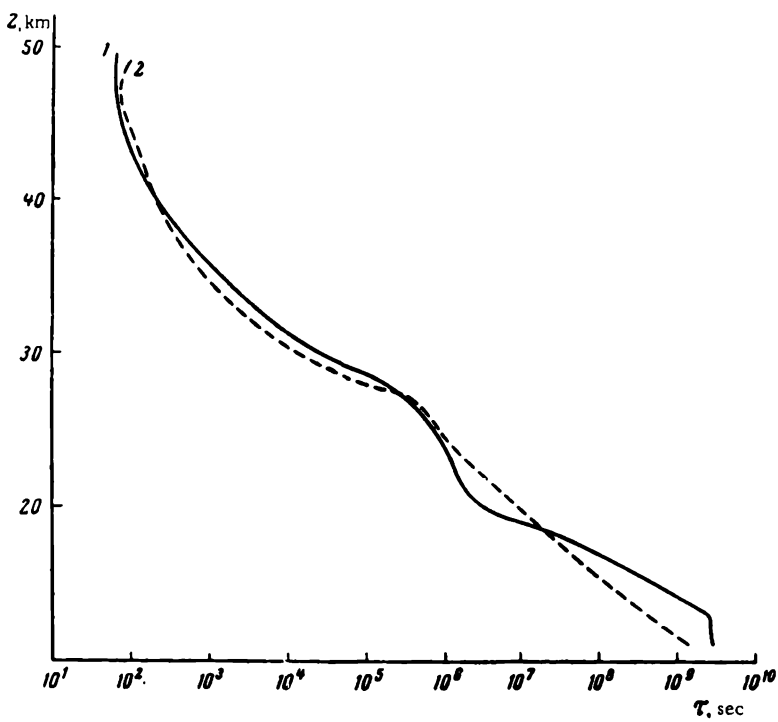

FIGURE 18. Time to photochemical ozone equilibrium as a function of height in the atmosphere;
1) for $x = 0.245$ cm; 2) for $x = 0.305$ cm.

The τ-values calculated for different ozone amounts can be plotted in two distribution curves (Figure 18), which intersect at altitudes of 42, 30

and 18.6 km. Similar intersections are observed for the ozone distribution curves, but the intersection altitudes are somewhat lower:

ρ curves	41 km	23.8 km	18.6 km
τ curves	42 "	30.2 "	17.6 "

If $\alpha = 1/\tau$ is known, the differential equation of the ozone concentration can be written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho w)}{\partial z} = \alpha (\rho_0 - \rho), \tag{5}$$

where w is the vertical velocity of air and ozone.

In a certain range of heights $\alpha = \alpha_0 e^{\lambda z}$. The density ρ_0 should be defined by some approximating function. Unfortunately, even with the simplest approximation, e.g., $\rho_0 = \rho_{00} e^{-\beta (z - z_0)^2}$, the integration cannot be performed analytically. We therefore resorted to the basic numerical-integration technique — the Runge method. An equilibrium ozone distribution was assumed as the initial condition, and the distributions were calculated for 6, 12, and 24 hours after the onset of circulation.

We analyzed some of the simplest vertical motions corresponding to definite atmospheric convergence and divergence conditions.

The following ascending motions were considered.

Case 1. The velocity w ($w > 0$) increases in the upward direction in inverse proportion to the air density ρ_a. If $\rho_a = \rho_0 e^{-\mu z}$, we have $w = w_0 e^{\mu z}$; the parameter w_0 is so chosen that at the 30 km level $w = 2$ cm/sec and $w = 10$ cm/sec.

The radial velocity associated with this kind of vertical motion is obviously zero.

Case 2. The velocity w increases in the upward direction according to Pogosyan's linear law, $w = w_0 + az$ ($a > 0$). The assumptions concerning ρ_a and ρ_0 remain as before. The equation of continuity in cylindrical coordinates is written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial (v_R R \rho)}{\partial R} + R \frac{\partial (w \rho)}{\partial z} = 0,$$

and since by assumption $\partial \rho / \partial t = 0$, we find

$$v_R = -\frac{R}{2} [a (1 - \mu z) - \mu w_0].$$

The radial motion in the lower layers is directed to the flow axis if $a > \mu w_0$ and away from the axis if $a < \mu w_0$; at fairly high altitudes it changes to upward-increasing divergence.

Case 3. The velocity is constant throughout the layer; if $w = 10$ cm/sec, we have

$$v_R = \frac{R \mu w}{2}.$$

Divergence is observed at all altitudes.

The following descending motions were considered.

Case 4. The downward velocity w $(w < 0)$ decreases as $w = w_0(z - z_0)e^{\mu z}$, i.e., the air diverges over the tropopause $z_0 = 11$ km. The parameter w_0 was chosen to provide $w = 10$ cm/sec and $w = 2$ cm/sec at the 30 km level. Then

$$v_R = -\frac{\rho_a}{\rho_0}\frac{Rw_0}{2},$$

i.e., the velocity of divergence decreases downward toward the tropopause in proportion to air density.

Case 5. The downward velocity decreases linearly, $w = w_0 + az$ $(a < 0)$. The expression for v_R is as in case 2 above.

Case 6. The velocity $w = w_0$ is constant through the layer. The convergence v_R is also constant through the layer, as in case 3 above.

Note that in all the preceding cases the velocities of divergence or convergence are proportional to the distance from the midpoint of the stream axis.

We now proceed with a discussion of the results of our calculations.*

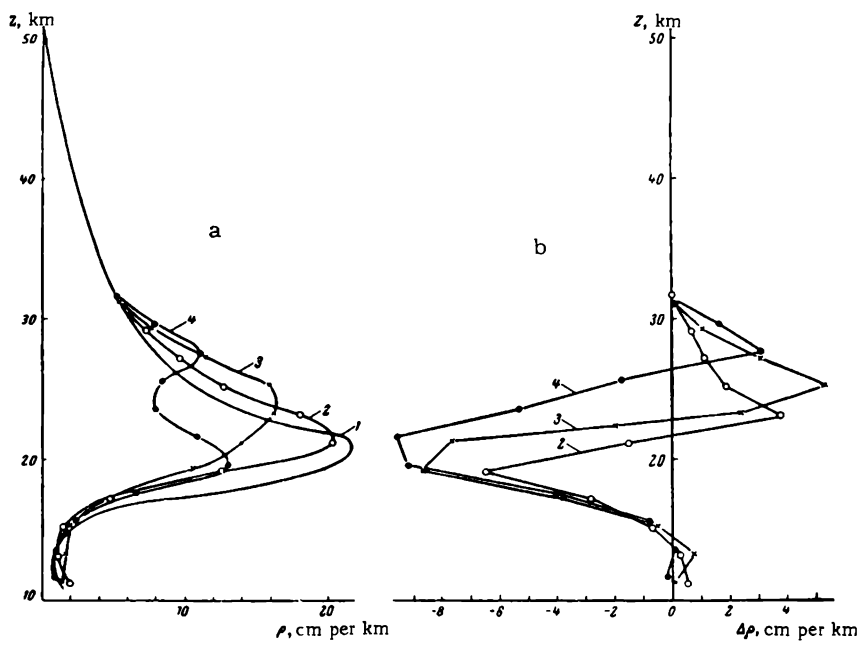

FIGURE 19. Vertical distribution of ozone concentration (a) and the change in concentration (b) for case 3A.
1) initial; 2) after 6 hrs; 3) after 12 hrs; 4) after 24 hrs.

Figure 19 plots the calculated ozone concentrations at different heights 6, 12, and 24 hours after the onset of circulation; the calculations were made for ascending motion ($w = \text{const}$, i.e., Case 3 above) for the lower ozone amount ($x = 0.245$ cm). The ozone concentration is seen to decrease

* The different cases of air motion are qualified by two symbols: A for $x = 0.245$ cm and B for $x = 0.305$ cm.

with time below the 22 km level, while increasing at higher altitudes. The entire ozone layer as if migrates upward. At heights above 31 km the effect of vertical motion is negligible. The general upward displacement is modified by an apparent splitting of the layer: ozone maxima appear at heights of 18 — 19 and 25 — 26 km.

The calculations for other types of ascending motions give analogous results concerning the migration of the layer and the general trend of the ρ distribution curve. A common feature is that ascending motions always raise the ozone concentration in the upper part of the layer and lower it at the bottom.

Of considerable interest are the different descending motions. Figures 20 and 21 present the results of our calculations for cases 4A and 4B; Figures 22 and 23 plot the corresponding curves for cases 6B and 6A.

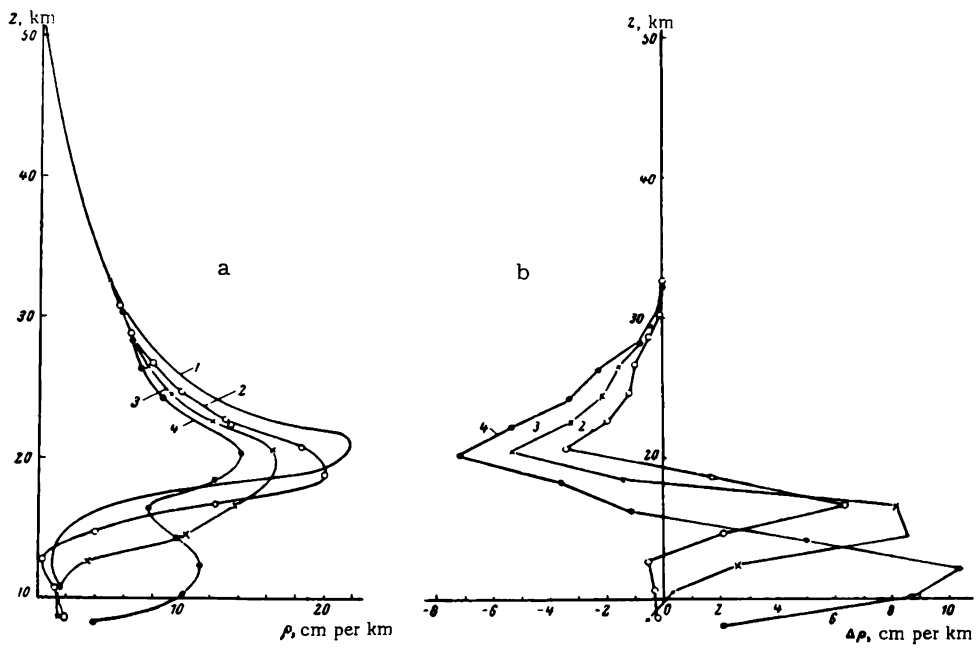

FIGURE 20. Vertical distribution of ozone concentration (a) and the change in concentration (b) for case 4A. Legend as in Figure 19.

In case 4, the descending and diverging streams produce the highest change in ozone amount, the ozone growth being particularly pronounced in the 11 — 18 km layer. The region of maximum growth and the boundary between the regions of increasing and decreasing ozone amounts gradually drop to lower altitudes. A secondary maximum, or even a second ozone layer forms fairly rapidly in the lower levels, immediately above the tropopause. The ozone reduction in the top part of the layer is also very substantial.

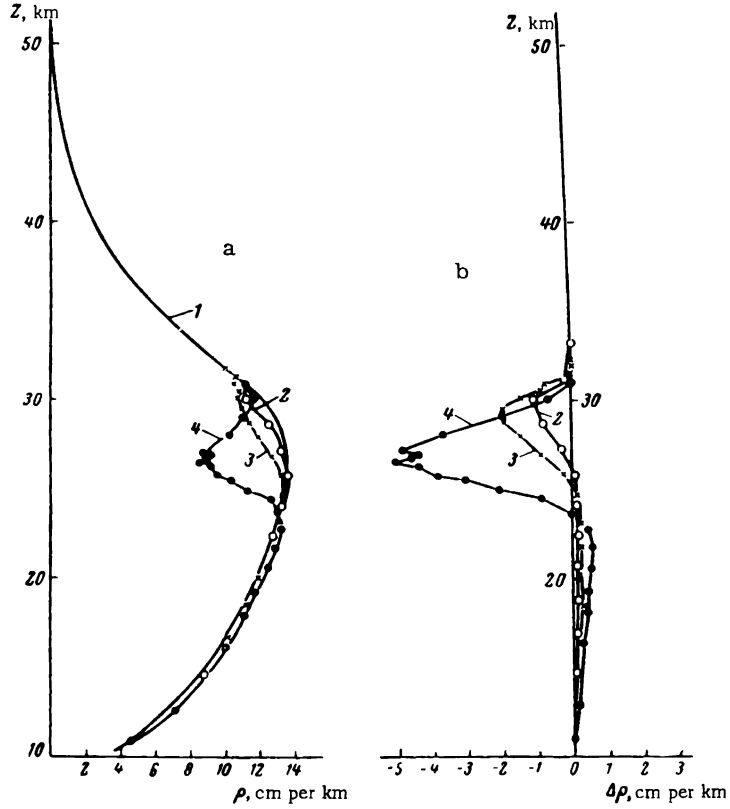

FIGURE 21. Vertical distribution of ozone concentration (a) and the change in concentration (b) for case 4B.
Legend as in Figure 19.

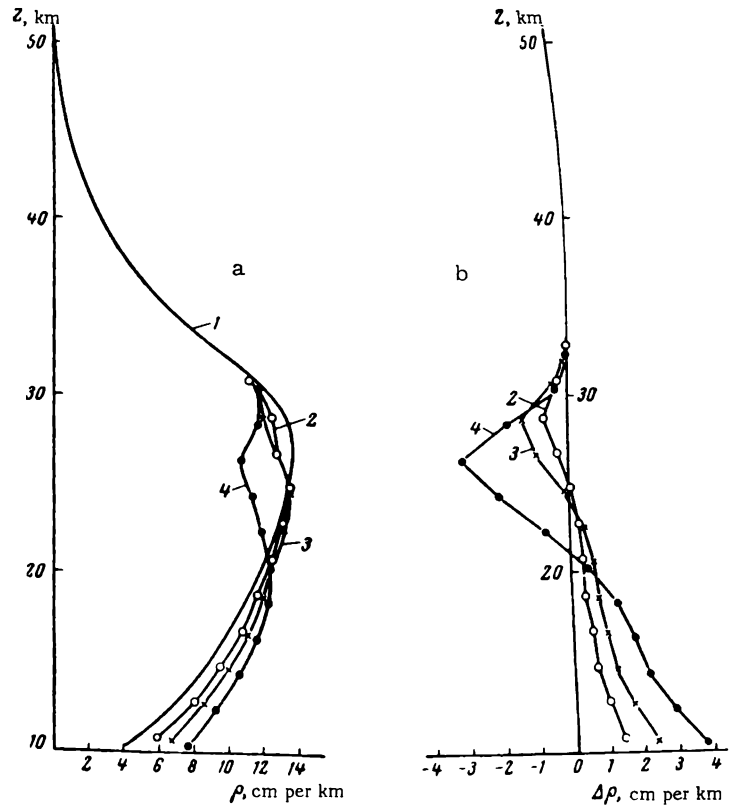

FIGURE 22. Vertical distribution of ozone concentration (a) and the change in concentration (b) for case 6B.
Legend as in Figure 19.

The ozone high is apparently more conservative with respect to vertical motions and the splitting of the ozone layer into two.

The results of our calculations suggest several conclusions concerning the variation of ozone caused by vertical motions.

Figures 19 through 23 show that within 24 hours the ozone is apparently in photochemical equilibrium above the h_1 level (32 — 33 km). At higher altitudes there is 0.034 cm of ozone (when $x = 0.245$ cm) or 0.047 cm (when $x = 0.305$ cm). Only a minor fraction of the ozone layer thus can be regarded as independent of vertical motions. Comparison of the results for 6, 12, and 24 hours after the onset of circulation indicates that the height h_1 gradually diminishes with time.

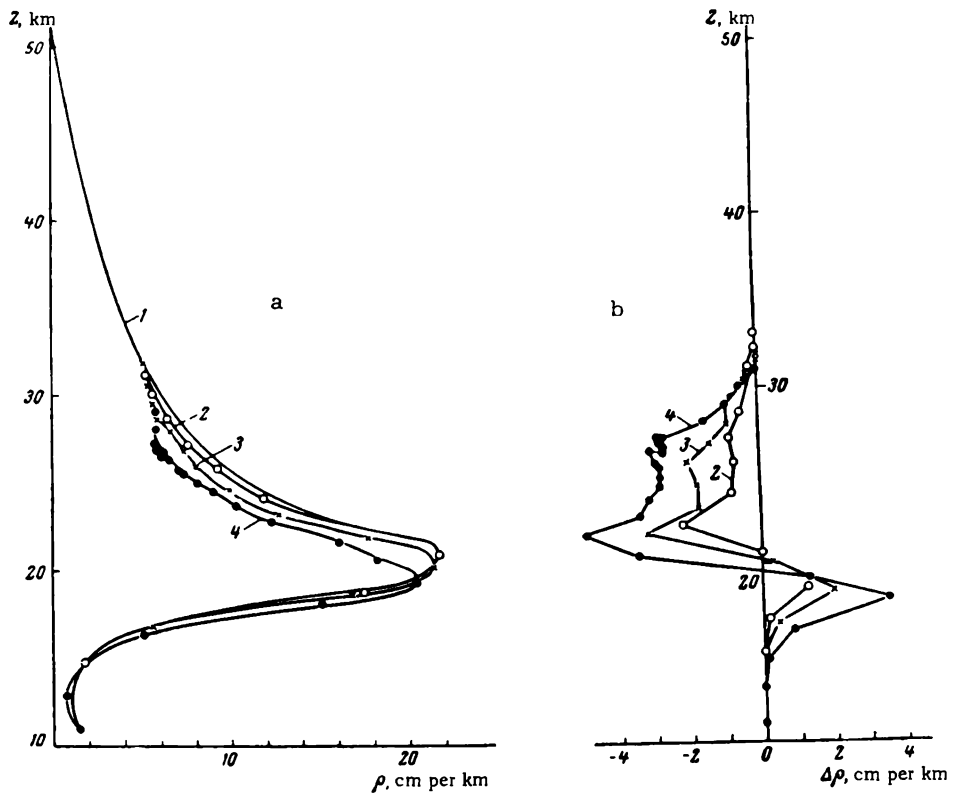

FIGURE 23. Vertical distribution of ozone concentration (a) and the change in concentration (b) for case 6A. Legend as in Figure 19.

The height h_2, below which the ozone is conserved, i.e., hardly affected by photochemical reactions in periods of up to 24 hours, is more difficult to determine. We can approximately estimate only the height of the level where the photochemical ozone changes by no more than 5% in 24 hours. In this sense, the ozone layer in cases 1A, 1B, 2A, and 2B is conserved up

TABLE 30. Variation of the total ozone for different cases of vertical motion, 10^{-3} cm

x, cm	Ascending motions								Descending motions							
	Case 1			Case 2			Case 3			Case 4			Case 5		Case 6	
	6 hrs	12 hrs	24 hrs	6 hrs	12 hrs	24 hrs	6 hrs	12 hrs	24 hrs	6 hrs	12 hrs	24 hrs	6 hrs	12 hrs	24 hrs	6 hrs	12 hrs	24 hrs
0.245	−1.6	−3.8	−3.9	−2.4	−7.0	−14.0	−10.0	−22.0	−42.0	−1.9	− 3.8	−15.0	+0.7	+1.5	− 2.2	+6.7	+10.2	+7.2
0.305	+1.4	+3.4	−5.0	−0.3	−1.4	−19.0	− 6.0	−17.0	−52.0	−5.9	−10.7	−19.0	−4.7	−3.4	−11.7	+2.4	+10.6	−3.8

to heights of 18.5—20 km, where it is transported mainly by horizontal currents. In cases 3A and 3B the conservation height drops to 15 km.

With ascending motions the lower-stratospheric ozone is thus conserved to an insignificant height, and the transport processes should be apparent at low altitudes, approximately at 150—120 mb levels. With descending motions, on the other hand, the height h_2 rises considerably, to 27—30 km. The effects of horizontal advection are very acutely felt in this case.

It is particularly interesting to calculate the total ozone in vertical motions of different signs. The results are shown in Table 30. We see from the table that ascending motions progressively reduce the ozone amount with time. This may explain the low ozone in the tropics, where general ascending motions persist for a long time. The reduction is faster the larger the initial ozone amount. In one case only, when the velocity increases exponentially and $x = 0.245$ cm, the ozone is seen to increase slightly at first, but then, within 24 hours, the trend is reversed to downward. The time rate of reduction is very large in cases 3A and 3B, being 0.042—0.052 cm/day. This explains the substantial day-by-day fluctuations of ozone in periods of rapidly changing synoptic conditions, e.g., when cyclones are replaced with anticyclones. The large variations in the total ozone observed in middle and especially in polar latitudes may therefore be attributed to the development of certain types of vertical motions.

Descending motions cause a more complex variation of x-values, which become more sensitive to the type of motion and to time. The increase in x-values is particularly pronounced in the case of constant descending velocity, for the lower total ozone (case 6A). The increase, however, is eventually replaced by a decrease in the ozone amount. The downward trend is prominent when the descending velocity diminishes toward the tropopause, mainly after long periods. Even in the most favorable case 6A the increase in ozone amount caused by descending motions is not as large as its reduction during ascending motions.

The effect of different types and velocities of descending motions on the ozone amount deserves a detailed theoretical investigation.

The simple models proposed by Paetzold and others are apparently insufficient. In particular,

the winter growth of ozone in the arctic region cannot be explained by descending motions alone. The following mechanism can be proposed: the ozone settles down in the anticyclone, and its amount markedly decreases in the upper strata above 20 km. A steep horizontal gradient is thus established between the anticyclone and the areas where the ozone does not descend. This may cause a rapid influx of ozone in the upper layers over the anticyclone; the total ozone is thus increased by a combination of vertical and horizontal circulation in the high layers.

We have already observed that descending motions which are damped by the tropopause do not raise the total ozone. To explain the variations in x-values, the tropospheric circulation should also be taken into consideration.

One of the main conclusions which follow from our calculations is that vertical motions, in particular descending currents, may indeed explain the origin of the secondary maxima in the vertical ozone distribution. These secondary maxima are frequently observed in nature. They may occur in the lower part of the ozone layer (as described in various sources) in the time of descending motions, and also in the top of the layer, where they are less prominent and comparatively difficult to observe. The low maximum at about 13 km altitude is particularly pronounced in case 6B, for the higher ozone amount. A somewhat less distinct maximum is observed near 16 km in case 5A. In case 4A no low maximum is observed, but there is a high-altitude maximum at 29 km, which is hardly noticeable in cases 5A and 6A.

Chapter Four

VARIATION OF THE TOTAL OZONE DURING TOTAL SOLAR ECLIPSE AND AN ATTEMPT AT ITS INTERPRETATION

Ozone measurements during solar eclipses are of considerable significance, since they provide information on the rate of photochemical reactions in the ozone layer and on the stability of ozone.

Total ozone measurements were carried out on 15 February 1961 from LI-2 aircraft in the Azov Sea area, near $\varphi = 46.2°N$, $\lambda = 35.7°E$. This point was in the region of the total solar eclipse. The aircraft flew back and forth at an altitude of 3000 m in the total eclipse zone; each leg of its course was some 70 km long and took 20 min. The observations were made to port and starboard, through open portholes. The Main Geophysical Observatory instrument with filters was used. The filter passbands were centered around 3120 and 3700 Å. The instrument was calibrated at the Main Geophysical Observatory using the Dobson spectrophotometer. The ozone amount was read off special nomograms computed for the appropriate flight altitudes.

The eclipse in the observation area began at $9^h 56^m$ Moscow Time (the first contact); the second contact was at $11^h 09^m$, and the third contact at $11^h 11^m$; the eclipse ended at $12^h 29^m$ (the fourth contact). The ozone observations started 43 min before the first contact and continued for 31 min after the fourth contact. During this time 68 total ozone readings were taken from the flying aircraft (11 before the eclipse, 44 during the eclipse, and 13 after the eclipse). The weather conditions were as follows. The aircraft flew above solid clouds: St cloudiness of 10 points strength extended at the 100—300 m level; a semitransparent Sc layer, also of strength 10, extended from 900 to 1200 m, below a strong temperature inversion: between 1.18 and 1.34 km the temperature rose from −7.2 to +2.5°, the humidity dropping from 92 to 50%. The clouds had a smooth, flat summit; the sky above the clouds was clear and bright, traces of Ci appearing near the north horizon toward the end of the eclipse. The sun remained unobscured throughout the measurements. The sky was initially light blue, the color deepening to nighttime blue as the eclipse progressed and the stars became visible. The temperature outside the portholes at the 3000 m altitude dropped to −9°, and the humidity 9—12%.

Additional standardizing and reference measurements of ozone were carried out from an aircraft on 14 February (flight altitude 5.2 km), 16 February (flight altitude from 3.2 to 4.2 km), and 18 February (flight altitude 2.0 km).

Table 31 and Figure 24 give the total ozone amount x, the number of observations n, the tropopause height h_{tr}, and the temperature at the

100 mb level on the relevant days. The ozone amounts were all reduced to the 3 km level. The lower 12 km layer was assumed /39/ to contain 8.5% of the total ozone, the ozone concentration being constant throughout. On the day of the eclipse, the concentration of ozone in the troposphere was 0.002 cm/km.

The total ozone during the relevant period dropped from 0.346 cm on 14 February to 0.280 cm on 16 February and again rose to 0.364 cm on 18 February. We see from Table 31 and Figure 24 that the usual correlation between x, h_{tr}, and T_{100} was observed on these days. Indeed, high ozone typically corresponds to a low tropopause and a warm stratosphere, and vice versa.

TABLE 31

Date, February 1961	x, cm	n	h_{tr}, km	T_{100}, °C
14	0.346	4	9.7	—51
15	0.319	68	10.3	—54
16	0.280	36	11.1	—59
17		—	10.3	—52
18	0.364	13	10.3	—57

At a first glance it may seem that the low ozone on 15 and particularly 16 February was unrelated to the total eclipse. On the other hand, a deep pressure trough extended over Crimea at the 100 mb level from 13 to 15 February. Strong northerly winds with speeds of up to 60—80 km/hour prevailed at the 100 mb level over USSR-in-Europe in this period. These weather conditions at the end of winter normally raise the ozone amount at the southern stations of the middle latitudes, but no such increase was observed in our case. The question of the fall in ozone on the day of the eclipse and on the next day thus remains open.

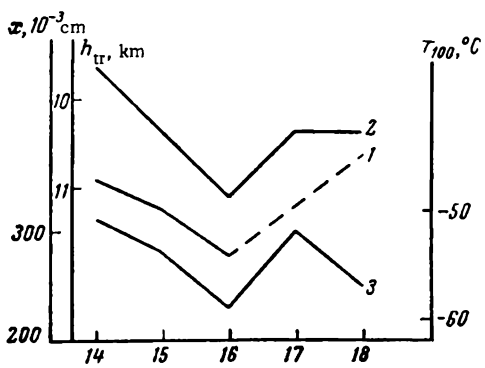

FIGURE 24. Variation of the ozone amount x (1), the tropopause height h_{tr} (2), and the temperature at the 100 mb level T_{100} (3) between 14 and 18 February 1961.

Let us now consider the actual x-values observed during the eclipse. Below we give the mean ozone amounts during different phases of the eclipse, and the standard deviations σ calculated for the corresponding periods:

	x, cm	σ, cm
Before the eclipse	0.338	0.010
During the eclipse	0.325	0.020
After the eclipse	0.283	0.015

The standard deviations σ during the eclipse were higher than the σ before the eclipse. The variance also increased after the eclipse.

Figure 25 plots the variation of x-values during the eclipse of the 15 February 1961, as recorded in the Azov Sea area. The vertical lines mark the different contacts. Curve 1 reveals some interesting features of the ozone amount during the eclipse. We shall concentrate only on those changes which are numerically greater than the standard deviations for the corresponding period.

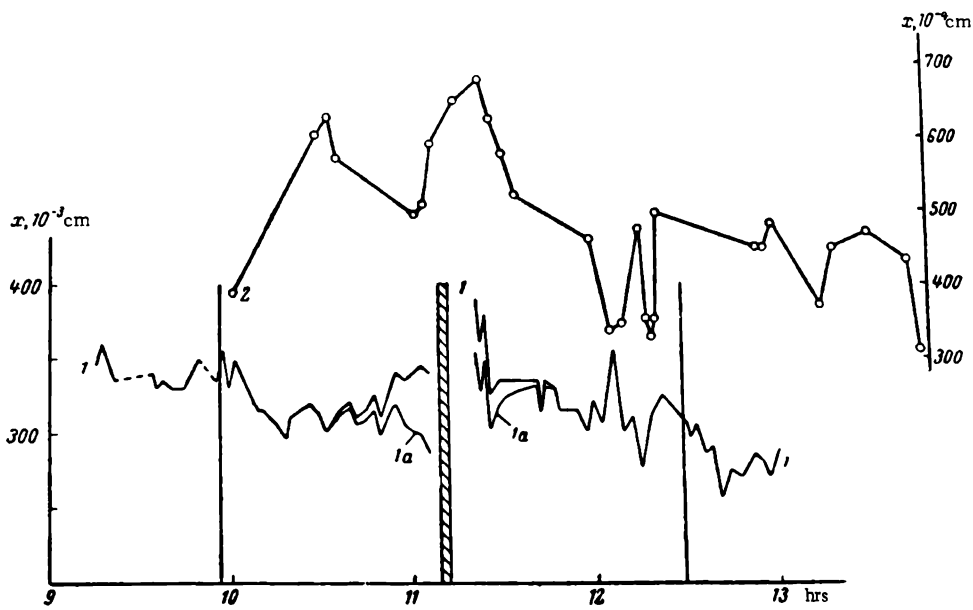

FIGURE 25. Variation of ozone during the total solar eclipse:
1) observations over the Azov Sea; 1a) ditto, corrected for limb darkening of the sun; 2) Rostov-on-Don observations. The vertical lines mark the different contacts of the eclipse. The cross-hatched band corresponds to the total eclipse.

(1) The ozone amount after the eclipse ($x = 0.283$ cm) is lower than before the eclipse ($x = 0.338$ cm). The decrement was 0.055 cm, or 17%.

(2) The x-values fall from the first to the second contact and increase toward the fourth contact.

(3) The reduction in x at the phases 0.4—1.0 changes to a phase-proportional growth of x-values.

(4) A distinct "peak" is observed near the central phase: it is clearly displaced to the right, displaying a certain lag relative to the eclipse. There is an impression of a rapid growth in x-values immediately after the third contact. This peak surpasses by 0.065 cm (20%) the mean x-value during the eclipse (0.325 cm) and by 0.095 cm (30%) the minimum ozone ($x = 0.295$ cm) during the eclipse.

The ozone becomes considerably more variable toward the fourth contact; there is a substantial reduction in ozone immediately after the fourth contact. A similar though less pronounced fall is observed before the first contact.

The ozone growth near the central phase may prove to be caused by the limb darkening of the sun. The limb darkening, i.e., lower radiation intensity of the solar limb, is more pronounced at the shorter wavelengths, so the measured ratio $\frac{I_{\lambda=3120}}{I_{\lambda=3700}}$ is lowered during the high phases of the eclipse even before the extinction of the solar spectrum in the ozone layer. This fact was commented upon back in 1957 by Svenson /49/, who calculated the apparent rise in the ozone amount during an eclipse for observations with a spectrophotometer. Steblova /17/ calculated this hypothetical increase in ozone amount from observations carried out on 15 February 1961 over the Rostov-on-Don area with an ISP-22 spectrograph. She found that at wavelengths of 3112 and 3320 Å the increment did not exceed 0.038 cm for the central phase, falling very rapidly to either side and becoming negligibly small at the 2/3 points.

Our instrument is not a spectrophotometer; it is equipped with broad-band filters, and Svenson's calculations do not apply. We therefore estimated the apparent increase in ozone during the central phase making use of Waldmeier's data /3/ on the limb reddening of the sun at different wavelengths. With our instrument, the apparent increment at the central phase did not exceed 0.060 cm. Applying the variation of the ozone increment for different phases of the eclipse from /17/, we plotted the graph of the ozone amount during the eclipse corrected for limb darkening (Figure 25, curve 1a). The limb darkening did not alter the fundamental features of the eclipse ozone curve, but the corrected curve reveals that the partial reduction in x-values after the first contact may persist until the total phase.

The Rostov-on-Don measurements are also shown in Figure 25 (curve 2). When comparing the different curves, it should be remembered that curve 2 has been shifted 8 min back to compensate for the time difference in the corresponding contacts. If we ignore the differences in the absolute ozone amounts and the differences in the overall variabilities of the curves, certain common features are seen to emerge. As in the Azov area, the ozone amount over Rostov-on-Don gradually drops from 0.50 cm during the eclipse to 0.42 cm after the eclipse. The two curves are peaked near the total phase, and both are somewhat displaced to the right. The x-values in both curves display stronger fluctuations before the fourth contact.

The sharp growth of x-values immediately after the eclipse was also reported by Bezverkhnii et al. /1/. A similar phenomenon was observed even earlier by Kawabata /38/, who reported a fall in ozone after the first contact. Overall reduction of x-values during an eclipse was also mentioned in /25, 34/. All this confirms the significance of the total

ozone features recorded during the eclipse; they are apparently associated with the redistribution of energy in the spectrum of the eclipsing sun.

Interpretation of the results involves considerable difficulties, since the redistribution of the ultraviolet energy in the solar spectrum outside the atmosphere is not known. The limb darkening indicates that the ozone should fall symmetrically about the central phase. The fall is attributed to the higher attenuation of the oxygen-dissociating wavelengths than the ozone-dissociating wavelengths. It depends on the time τ to photochemical equilibrium in the upper part of the ozone layer. The available estimates of τ (see Chapter Three) give a very small ozone reduction. However, the current research on atmospheric ozone under conditions of variable solar radiation will possibly lead to a revision of the τ-values.

The ozone in our case was seen to decrease at least during the first half of the eclipse. The increase in ozone immediately after the second phase is difficult to explain. The ozone variation is close to the theoretical results obtained by Dütsch /22/ for the ozone amount during sunset, when the radiation conditions in the upper atmosphere change rapidly.

In conclusion the authors extend their thanks to N. A. Petrenko and A. F. Nepovitova, who devoted much effort to the reduction and the analysis of the IGY ozone data: their help was indispensable in the compilation of the tables. The work was carried out in 1961—1963 at the Department of the Physics of the Atmosphere of the Moscow State University according to the IGY program and the schedule set up for the reduction of the IGY data.

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* [For Russian abbreviations in this Bibliography, see Explanatory List on p. 90.]

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APPENDIX I. Maximum and minimum ozone and the amplitude of x-values at Arosa, 10^{-3} cm

Year	Maximum												Minimum												Amplitude											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1926	—	—	—	—	—	—	238	246	222	237	228	275	—	—	—	—	—	—	215	189	183	158	185	197	—	—	—	—	—	—	23	57	39	79	43	78
1927	319	299	313	293	295	275	266	260	245	236	238	262	202	221	222	238	237	224	224	203	196	176	165	194	117	78	91	55	58	51	42	57	49	54	73	68
1928	275	270	267	296	303	270	232	227	229	216	224	247	192	207	224	191	236	213	204	194	173	172	170	201	83	63	43	105	67	57	28	33	56	44	54	46
1929	283	333	277	369	290	264	—	—	—	—	—	—	199	223	216	239	232	230	—	—	—	—	—	—	84	110	61	130	58	34	—	—	—	—	—	—
1930	—	—	—	—	—	—	—	238	—	—	—	—	—	—	—	—	—	—	—	187	—	—	—	—	—	—	—	—	—	—	—	51	—	—	—	—
1931	—	—	—	—	—	—	—	246	255	215	220	251	—	—	—	—	—	—	—	203	208	187	182	169	—	—	—	—	—	—	—	43	47	28	38	82
1932	262	326	298	295	298	260	264	236	231	244	217	213	203	204	240	251	221	224	217	199	187	167	197	184	59	122	58	44	77	36	47	37	44	77	20	29
1933	297	340	344	293	319	297	270	246	237	239	253	278	202	171	216	238	249	246	216	209	198	200	203	194	95	169	128	55	70	51	54	37	39	39	50	84
1934	278	310	319	308	285	273	249	260	217	257	233	253	203	183	245	211	246	230	216	209	189	188	178	186	75	127	74	97	39	43	33	51	28	69	55	67
1935	286	345	334	333	294	255	272	233	221	209	231	254	186	236	207	212	234	192	217	211	186	188	187	197	100	109	127	121	60	63	55	22	35	21	44	57
1936	308	315	303	326	287	290	250	245	252	264	234	257	194	231	246	229	238	225	217	202	180	178	188	175	114	84	57	97	49	65	33	43	72	86	46	82
1937	271	299	365	302	298	264	249	238	245	214	220	282	225	221	224	247	231	221	216	214	200	192	185	201	46	78	141	155	67	43	33	24	45	22	35	81
1938	308	326	282	257	290	259	252	241	234	212	224	244	216	215	197	222	250	219	218	215	193	179	177	172	92	111	85	135	40	40	34	26	41	33	47	72
1939	252	288	341	260	291	267	268	231	220	264	238	253	178	195	218	204	238	219	214	209	189	186	174	198	74	93	123	56	53	48	54	22	31	78	64	55
1940	335	361	358	344	317	312	272	256	246	243	249	261	229	253	257	261	263	249	218	209	203	188	180	199	106	108	101	83	54	63	54	47	43	55	69	62
1941	279	351	335	315	325	295	277	276	250	282	282	251	209	186	257	242	266	224	228	211	199	190	187	180	70	65	78	73	59	71	49	65	51	92	95	71
1942	340	366	300	354	359	282	254	244	223	233	252	263	206	247	235	235	219	227	215	206	187	158	176	185	134	119	65	119	140	55	39	38	36	75	76	78
1943	273	296	302	285	268	301	262	237	234	218	259	263	195	187	230	230	231	228	224	194	190	187	195	202	78	109	72	55	37	73	38	43	44	31	64	61
1944	223	301	315	284	270	279	246	237	238	238	252	256	185	185	229	207	221	233	209	200	191	184	186	196	38	116	130	77	49	46	37	37	47	54	66	60
1945	303	286	303	293	338	277	277	254	262	238	328	261	211	231	219	241	242	229	217	203	177	186	194	188	92	55	84	52	96	48	60	59	51	52	34	73
1946	293	295	314	276	270	267	238	240	211	270	236	245	199	205	239	239	216	227	211	212	182	181	186	200	94	90	75	37	54	40	27	28	29	89	50	45
1947	304	304	332	301	283	276	258	243	243	221	253	266	236	238	238	234	239	228	213	210	185	197	171	177	68	66	94	67	44	48	45	33	58	24	82	89
1948	312	369	280	291	274	274	281	248	241	260	235	257	188	205	199	238	230	227	223	204	185	176	171	208	124	64	81	53	44	47	58	44	56	84	64	49
1949	279	306	317	320	314	273	261	260	234	207	233	246	202	194	213	217	239	235	219	203	180	175	185	174	77	104	104	103	75	38	42	57	54	32	48	72
1950	299	310	301	323	287	265	256	254	229	232	268	268	203	211	195	220	233	221	196	202	196	174	176	197	96	99	106	103	54	44	60	52	33	58	92	71
1951	279	372	331	313	296	298	259	240	235	225	220	250	215	234	251	246	249	235	216	214	191	187	168	194	64	138	80	67	47	63	43	26	44	38	52	56
1952	337	315	309	316	301	280	256	251	240	233	231	261	208	232	259	243	256	228	223	202	205	202	202	206	129	83	50	73	45	52	33	49	35	31	29	55
1953	298	345	310	300	330	302	269	252	229	—	220	—	191	192	243	243	227	234	213	214	188	—	170	—	107	153	67	57	103	68	56	38	41	—	50	—
1954	—	—	330	337	309	279	275	264	232	227	234	222	—	—	224	264	244	234	227	221	208	189	178	171	—	—	106	73	65	45	48	53	24	38	56	51
1955	272	305	315	313	298	292	252	265	256	220	216	251	186	227	218	239	221	230	228	217	196	190	167	195	86	78	97	74	77	62	24	48	60	30	49	56
1956	262	322	332	298	288	266	248	238	216	230	212	274	216	246	211	257	229	240	210	196	185	177	181	181	46	106	121	41	59	26	38	42	31	53	31	93
1957	302	280	278	323	313	266	246	233	237	223	236	271	185	206	211	214	236	222	214	210	190	177	183	198	117	74	67	109	77	44	32	23	47	46	53	73
1958	298	373	328	375	290	290	279	259	248	262	242	261	198	208	248	245	248	226	222	219	197	200	185	185	100	165	80	130	42	64	57	40	51	62	67	76
	Many-year maxima												Many-year minima																							
	340	372	365	375	359	312	281	276	262	282	282	282	178	171	195	191	216	192	196	187	173	158	165	169												

APPENDIX II. Monthly ozone amounts at IGY stations in 1957–1959, 10^{-3} cm

No.	Stations	φ°	1957						1958												1959											
			VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
			Northern Hemisphere																													
1	SP-6	83.8	—	—	—	—	—	—	—	—	—	534	498	378	319	306	—	—	—	—	—	—	—	—	425	329	206	—	—	—	—	—
2	Kheis Isl.	82.5	322	298	292	235	259	264	376	444	530	469	430	353	331	289	299	318	366	—	—	—	—	—	428	401	273	—	—	—	—	—
3	Alert	80.1	—	—	—	—	—	—	—	—	—	—	373	344	313	274	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
4	Murchison	78.1	339	315	290	324	—	—	—	—	—	—	—	382	365	336	340	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5	Longyearbyen	74.7	346	315	319	320	337	304	375	502	499	488	422	376	346	307	322	341	433	322	310	413	505	486	439	371	325	321	315	311	282	355
6	Resolute Bay	73.5	425	382	—	—	—	—	—	—	—	525	574	445	336	308	—	342	—	—	—	—	—	422	397	312	284	264	260	—	—	—
7	Dikson	69.6	308	305	291	278	283	275	336	476	469	425	399	361	323	287	289	279	299	293	343	377	405	442	388	369	317	301	280	266	281	—
8	Tromsö	64.1	322	314	297	303	—	301	345	419	427	407	400	347	331	326	302	306	272	338	—	396	439	427	367	366	337	315	277	286	—	—
9	Reykjavik	60.2	343	323	311	277	291	—	—	407	412	398	414	357	346	325	290	292	257	265	376	344	413	419	376	360	330	306	283	283	310	298
10	Lerwick	59.9	357	340	327	307	295	—	—	459	467	434	389	365	357	344	302	280	268	—	388	377	391	443	414	390	340	328	307	301	306	—
11	Voeikovo	59.8	323	316	317	282	262	275	331	430	453	414	372	352	334	312	283	281	258	322	—	—	—	—	—	—	—	—	—	—	—	—
12	Uppsala	56.1	370	356	349	298	302	318	370	450	482	440	402	395	366	337	310	308	300	356	422	393	428	437	410	391	356	326	316	312	312	315
13	Aarhus	55.7	412	335	346	347	283	284	360	390	402	389	378	367	397	—	325	302	282	273	310	340	344	380	434	393	350	320	320	—	—	—
14	Moscow	55.3	—	—	—	289	296	300	343	381	417	387	400	367	357	335	298	300	287	344	375	—	413	420	388	369	337	312	294	293	314	333
15	Eskdalemuir	53.6	327	308	276	281	294	315	317	—	431	425	366	352	339	300	315	293	353	357	383	417	437	426	402	361	337	336	312	311	307	337
16	Edmonton	52.4	306	342	316	304	293	314	353	404	373	388	332	345	322	302	292	262	—	—	—	—	310	314	319	302	269	288	278	301	—	—
17	Potsdam	51.8	350	340	306	273	296	295	345	353	399	402	400	381	361	337	293	292	284	318	379	349	400	406	397	372	351	324	308	299	304	308
18	Oxford	51.3	337	336	324	304	310	348	360	420	401	440	407	391	362	346	319	318	362	387	409	460	464	446	387	373	374	315	322	327	355	386
19	Moosonee	50.8	304	297	305	260	333	—	—	—	350	390	378	340	345	—	271	281	245	248	—	—	—	—	—	—	—	—	—	—	—	—
20	Uccle	50.2	325	304	279	250	280	290	325	347	370	378	378	357	337	318	284	282	277	340	—	—	—	386	370	347	330	302	289	280	303	285
21	Camborne	48.8	327	327	305	274	312	306	376	377	414	410	367	364	331	311	286	294	309	372	396	367	402	394	387	354	335	323	313	305	322	354
22	Paris (Montsouris)	46.9	—	—	—	—	—	—	—	—	—	364	385	371	345	326	296	294	310	353	385	401	417	389	374	357	333	—	—	—	—	—
23	Caribou	46.8	314	307	286	265	282	315	347	338	393	400	359	351	337	313	288	292	289	309	349	346	347	368	367	352	324	313	298	280	284	310
24	Arosa	46.8	296	288	280	253	262	306	334	375	394	403	354	354	339	296	293	285	319	327	354	404	414	390	380	329	331	305	287	301	309	347
25	Bismarck	44.5	—	—	—	—	—	—	—	—	381	380	361	341	315	305	279	277	393	350	390	409	407	399	353	338	337	293	298	268	318	338
26	Green Bay	43.3	—	—	—	—	272	250	292	330	365	401	339	305	252	233	231	244	244	281	304	—	—	—	300	292	286	284	239	242	253	246
27	El'brus																															

28	Alma-Ata	43.3	—	—	—	—	243	233	280	304	289	281	286	282	258	240	247	252	247	286	—	—	—	—	328	314	311	328	291	274	245	215
29	Vladivostok	43.1	—	270	278	268	301	—	—	—	—	257	322	263	257	285	269	319	292	288	330	345	384	394	400	363	305	285	266	286	295	294
30	Sapporo	43.1	—	—	—	—	—	—	—	435	464	428	417	381	330	318	303	323	328	402	452	430	433	423	405	397	329	299	314	316	349	388
31	Vigna di Valle	42.1	326	314	305	292	302	330	360	371	412	419	366	359	383	313	307	298	313	329	366	370	368	387	381	354	324	327	320	310	309	354
32	Abastumani	41.8	278	271	258	272	280	296	314	358	366	352	309	311	287	287	266	260	276	300	309	410	355	363	329	296	291	306	297	292	275	287
33	Naples	40.9	—	—	—	—	—	—	—	—	—	—	—	—	299	272	274	262	285	311	—	—	—	—	—	—	—	—	—	—	—	—
34	Elmas	39.2	279	304	291	294	295	302	322	328	334	364	336	329	302	296	297	285	306	319	324	334	345	354	358	—	—	—	—	—	—	—
35	Washington	38.9	325	321	292	305	290	298	330	366	360	366	366	337	325	320	294	299	285	316	336	342	365	—	—	—	—	—	—	—	—	—
36	Messina	38.2	267	329	314	308	318	331	356	377	329	353	348	361	337	326	330	303	328	363	—	—	—	—	—	—	—	—	—	—	—	—
37	Tateno	36.0	313	286	289	275	275	316	322	341	392	366	356	341	315	297	285	283	278	311	326	340	358	358	369	368	322	305	293	285	283	308
38	Srinagar	34.1	264	263	265	—	260	254	280	291	293	290	304	292	270	271	258	257	250	354	288	289	294	285	274	272	261	257	258	249	259	281
39	Habbaniyah	33.4	293	289	286	280	294	295	313	339	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
40	Fort Worth	32.7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	359	345	322	302	284	297	306	
41	Kagoshima	31.6	—	—	—	—	—	—	—	—	327	340	320	329	298	281	275	271	260	289	287	298	322	—	—	—	284	289	279	278	261	271	
42	Torishima Isl.	30.5	—	—	—	—	254	262	279	292	336	339	341	332	320	300	284	261	245	257	259	281	304	306	327	318	292	278	269	262	248	255
43	Quetta	30.2	212	211	220	220	218	231	245	253	309	311	314	298	282	288	276	272	271	291	259	259	280	281	281	277	267	258	254	246	260	268
44	Delhi	28.6	243	255	261	247	229	240	266	268	268	252	242	256	252	245	242	246	243	267	275	275	269	272	254	257	246	245	244	251	255	259
45	Benares	25.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
46	Mount Abu	24.6	230	229	229	226	218	224	241	243	259	256	248	253	246	238	242	237	232	242	247	244	245	257	254	261	—	—	249	247	237	242
47	Marcus Isl.	24.3	—	—	—	—	—	—	232	243	252	270	294	298	294	283	270	272	256	251	246	266	267	296	311	310	303	298	288	273	263	244
48	Tamanrasset	22.8	—	—	—	229	251	186	173	195	227	258	214	192	170	212	212	213	200	193	—	—	307	298	301	—	—	—	—	—	—	—
49	Mauna Loa	19.5	—	—	—	—	—	260	256	251	270	285	288	284	271	271	268	264	257	253	251	265	276	292	307	310	286	285	276	264	—	—
50	Kodaikanal	10.2	235	237	239	237	215	220	225	222	233	247	239	247	245	244	241	239	237	217	226	238	239	248	260	262	266	266	260	254	237	231
	Southern Hemisphere																															
51	Leopoldville	4.4	—	—	—	—	—	—	257	252	251	248	236	244	247	248	254	254	251	244	274	272	272	277	278	287	—	—	—	—	—	—
52	Brisbane	27.5	295	302	333	303	301	302	291	274	281	—	—	—	—	319	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
53	Aspendale	38.0	340	351	364	352	333	317	313	296	298	282	296	347	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
54	Wellington	41.3	314	329	349	342	347	310	294	271	261	270	281	319	346	339	370	364	333	289	—	—	—	—	—	—	—	—	—	—	—	—
55	Port-aux-Français	49.4	—	441	438	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
56	Macquarie Isl.	54.5	356	353	373	428	381	—	334	299	332	342	337	395	378	412	414	435	392	365	—	—	—	—	—	—	—	—	—	—	—	—
57	Oasis — Mirnyi	66.5	—	—	—	—	—	—	278	333	330	—	—	—	—	—	496	488	447	442	—	—	—	—	—	—	—	—	—	—	—	—
58	Dumont d'Urville	66.7	—	—	—	—	—	—	—	233	239	277	234	325	307	264	184	255	311	252	—	—	—	—	—	—	—	—	—	—	—	—
59	Halley Bay	75.5	273	298	—	319	394	346	332	300	281	254	—	256	266	—	288	301	350	382	—	—	—	—	—	—	—	—	—	—	—	—
60	Little America	78.2	346	536	285	342	412	—	310	296	—	—	—	—	—	—	—	335	—	—	—	—	—	—	—	—	—	—	—	—	—	—

APPENDIX III. Maximum and minimum ozone at IGY stations in 1957 –1958, 10^{-3} cm

No	Stations	Daily mean					
		1957					
		VII	VIII	IX	X	XI	XII
1	SP-6, SP-8	—	—	—	—	—	—
2	Kheis Isl.	—	—	—	—	—	—
3	Alert	342	315	310	252	311	316
4	Murchison	—	—	—	—	—	—
5	Longyearbyen	339	315	290	324	—	—
6	Resolute Bay	387	353	334	—	356	332
7	Dikson	493	436	—	—	—	—
8	Tromsö	358	329	315	364	347	351
9	Reykjavik	331	341	330	380	—	392
10	Lerwick	413	362	387	319	365	—
11	Voeikovo	399	366	364	321	304	—
12	Uppsala	365	341	354	320	331	365
13	Aarhus	444	406	393	341	354	404
14	Moscow	495	426	447	421	353	410
15	Eskdalemuir	—	—	—	351	380	355
16	Edmonton	371	334	318	337	351	376
17	Potsdam	350	403	368	331	338	318
18	Oxford	387	381	353	351	370	363
19	Moosonee	370	374	380	339	396	401
20	Uccle	328	308	355	300	348	—
21	Cambome	380	350	326	321	328	348
22	Paris (Montsouris) (midday data)	360	347	360	343	377	340
23	Caribou	—	—	—	—	—	—
24	Arosa	348	324	—	—	329	370
25	Bismarck	31—	30—	32—	29—	31—	38—
26	Green Bay	—	—	—	—	—	—
27	El'brus	—	—	—	—	—	297
28	Vladivostok	—	289	309	301	328	—
29	Sapporo	—	—	—	—	—	—
30	Alma-Ata	—	—	—	—	266	263
31	Vigna di Valle	390	352	344	318	351	400
32	Abastumani	292	295	287	301	296	312
33	Elmas	329	348	321	339	348	347
34	Washington	35—	34—	35—	34—	32—	37—
35	Messina	347	361	386	364	395	398
36	Tateno	368	305	325	305	309	358
37	Srinagar	297	281	282	—	303	287
38	Habbaniyah	305	306	299	293	313	364
39	Fort Worth	—	—	—	—	—	—
40	Kagoshima	—	—	—	—	—	—
41	Torishima Isl.	—	—	—	—	263	285
42	Quetta	241	232	245	252	243	270
43	Delhi	267	287	270	268	254	253
44	Mount Abu	242	238	241	238	234	238
45	Marcus Isl.	—	—	—	—	—	—
46	Tamanrasset (once a day)	—	—	—	253	303	242
47	Mauna Loa	—	—	—	—	—	294
48	Kodaikanal	242	241	247	243	224	229
49	Leopoldville	—	—	—	—	—	—
50	Brisbane	352	352	344	365	338	320
51	Aspendale	409	429	430	408	385	359
52	Wellington	368	383	377	384	386	348
53	Macquarie Isl.	—	—	—	—	—	—
54	Oasis	—	—	—	—	—	—
55	Port-aux-Francais	—	—	—	—	—	—
56	Dumont d'Urville	—	—	—	—	—	—
57	Halley Bay	276	302	—	381	428	393
58	Little America	376	—	407	500	462	—

maxima

1958

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
—	—	—	562	570	415	355	—	—	—	—	—
—	—	576	519	596	376	398	375	310	—	—	—
—	466	607	552	530	410	346	319	322	343	409	—
—	—	—	—	404	379	353	296	—	—	—	—
—	—	—	—	—	382	365	336	340	—	—	—
—	541	568	549	471	433	382	331	376	354	537	354
—	—	—	594	626	479	437	326	—	432	—	—
520	530	558	510	424	407	371	322	332	320	365	400
540	570	517	451	431	406	369	369	364	363	313	—
—	513	505	452	464	398	390	358	341	344	316	297
—	476	516	476	452	399	387	375	350	303	306	—
496	507	553	438	435	406	411	344	342	330	312	436
475	560	580	568	441	432	423	382	358	363	367	405
422	444	462	481	480	370	454	—	366	370	325	340
464	488	500	434	455	409	396	359	329	336	337	422
367	—	468	491	417	384	381	348	367	354	414	420
396	456	—	403	393	386	344	344	370	297	—	—
467	480	473	475	442	417	406	376	330	342	338	408
436	491	460	500	522	441	400	399	369	392	480	437
—	—	379	390	471	357	393	—	306	324	256	471
392	372	430	458	430	390	384	359	344	330	364	450
534	564	509	513	438	435	388	371	337	319	394	534
—	—	—	414	432	423	381	399	369	356	371	411
444	505	507	511	394	398	381	352	332	351	334	351
382	477	494	489	409	468	400	347	389	373	376	384
—	—	457	425	399	389	346	334	328	333	410	387
323	351	448	417	464	378	331	280	249	286	312	297
—	—	—	403	365	278	274	298	300	343	326	299
—	504	573	500	481	460	387	354	331	380	395	486
294	326	326	308	313	303	292	295	279	281	247	—
444	470	517	497	449	410	382	333	335	359	357	376
345	422	382	381	369	380	311	341	290	304	311	323
377	456	416	403	414	372	364	313	309	321	349	389
365	423	425	415	408	398	379	434	325	356	325	353
471	427	490	506	419	408	411	353	362	386	390	418
374	378	504	445	410	381	349	327	325	305	346	395
311	308	334	326	336	338	282	289	271	278	269	296
393	383	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	382	405	354	373	334	308	292	284	297	341
300	320	367	402	384	390	359	341	301	292	260	286
296	341	349	368	394	329	292	300	287	316	310	321
296	312	309	286	266	298	276	260	263	256	259	286
254	268	284	276	261	266	262	246	255	250	243	262
243	259	280	312	306	313	306	300	280	283	268	271
200	246	273	307	252	210	202	245	248	242	253	217
266	273	293	301	305	297	278	280	274	271	274	269
234	230	250	256	251	254	252	250	251	244	241	227
265	271	272	264	260	255	259	255	266	271	289	283
324	305	307	—	317	345	353	358	400	375	343	338
334	340	334	311	328	377	474	435	475	445	396	347
362	307	292	298	325	371	387	389	392	409	366	330
406	338	381	388	387	429	448	456	474	522	448	420
314	356	360	—	—	—	—	—	528	508	448	—
—	—	—	—	—	—	—	—	—	—	—	—
—	270	360	430	389	460	430	300	305	420	530	330
358	336	341	264	—	269	281	—	318	328	402	419
373	313	—	—	—	—	—	—	—	392	—	—

APPENDIX III (cont.). Maximum and minimum ozone at IGY stations in 1957–1958, 10^{-3} cm

No.	Stations	Absolute					
		1957					
		VII	VIII	IX	X	XI	XII
1	SP-6, SP-8	—	—	—	—	—	—
2	Kheis Isl.	—	—	—	—	—	—
3	Alert	349	330	314	—	311	316
4	Murchison	—	—	—	—	—	—
5	Longyearbyen	347	317	295	324	—	—
6	Resolute Bay	397	362	—	—	362	332
7	Dikson	504	439	—	—	—	—
8	Tromsö	358	343	320	378	347	351
9	Reykjavik	348	382	341	367	—	392
10	Lerwick	413	370	461	330	366	—
11	Voeikovo	434	382	364	352	309	—
12	Uppsala	365	341	354	327	331	365
13	Aarhus	460	416	430	356	371	424
14	Moscow	—	—	—	—	—	—
15	Eskdalemuir	—	—	—	351	385	—
16	Edmonton	376	340	318	346	351	400
17	Potsdam	380	412	370	340	340	318
18	Oxford	402	398	362	354	370	363
19	Moosonee	390	383	384	339	400	401
20	Uccle	329	309	356	319	348	—
21	Cambome	470	393	339	341	338	348
22	Paris (Montsouris) (midday data)	—	—	—	—	—	—
23	Caribou	—	—	—	—	—	—
24	Arosa	348	334	—	—	329	373
25	Bismarck	310	300	320	290	310	380
26	Green Bay	—	—	—	—	—	—
27	El'brus	—	—	—	—	—	297
28	Vladivostok	—	289	320	312	338	—
29	Sapporo	—	—	—	—	—	—
30	Alma-Ata	—	—	—	—	278	291
31	Vigna di Valle	403	380	351	343	396	415
32	Abastumani	303	303	299	318	303	326
33	Elmas	371	381	374	434	362	400
34	Washington	35—	35—	35—	35—	32 —	38—
35	Messina	427	427	410	445	425	430
36	Tateno	379	333	340	316	325	362
37	Srinagar	305	287	286	—	303	287
38	Habbaniyah	305	306	299	293	313	364
39	Fort Worth	—	—	—	—	—	—
40	Kagoshima	—	—	—	—	—	—
41	Torishima Isl.	—	—	—	—	268	297
42	Quetta	260	286	295	279	246	282
43	Delhi	267	287	275	271	258	258
44	Mount Abu	242	238	241	238	238	238
45	Marcus Isl.	—	—	—	—	—	—
46	Tamanrasset (once a day)	—	—	—	—	—	—
47	Mauna Loa	—	—	—	—	—	299
48	Kodaikanal	252	244	257	244	224	230
49	Leopoldville	—	—	—	—	—	—
50	Brisbane	—	—	—	—	—	—
51	Aspendale	409	429	430	419	445	370
52	Wellington	—	—	—	—	—	—
53	Macquarie Isl.	—	—	—	—	—	—
54	Oasis	—	—	—	—	—	—
55	Port-aux-Francais	—	—	—	—	—	—
56	Dumont d'Urville	—	—	—	—	—	—
57	Halley Bay	—	—	—	387	439	398
58	Little America	—	—	407	507	488	—

maxima

1958											
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
—	—	—	595	580	430	380	—	—	—	—	—
—	—	620	590	640	400	420	420	310	—	—	—
609	466	607	553	550	416	352	326	327	—	—	—
—	—	—	—	—	379	353	—	—	—	—	—
—	—	—	—	—	393	366	339	343	—	—	—
—	541	574	549	512	448	395	342	376	356	537	354
—	—	—	620	656	502	485	316	—	505	—	—
520	530	558	510	424	409	371	324	332	320	—	—
540	580	546	479	454	421	373	370	364	—	317	—
—	513	510	466	526	409	421	399	378	352	321	—
—	484	536	491	452	409	417	409	350	329	306	—
496	507	553	466	435	406	411	344	342	330	312	436
485	613	587	590	508	434	444	389	370	375	374	410
—	—	—	—	—	—	—	—	—	—	—	—
464	505	500	434	455	409	399	374	330	337	337	422
367	—	469	508	436	390	389	360	387	363	426	429
397	433	—	408	390	392	347	348	320	301	—	—
467	485	486	484	442	424	412	395	332	350	338	408
446	500	460	514	531	452	516	491	412	408	519	444
—	—	379	412	475	364	390	—	306	325	287	475
392	385	468	479	489	414	391	371	382	350	366	450
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	416	433	423	390	431	427	358	371	438
452	512	517	521	403	403	383	352	337	351	334	353
406	477	478	469	416	440	446	404	513	382	388	404
—	—	465	442	405	416	355	343	334	337	—	—
379	395	464	458	479	414	343	317	273	288	319	306
—	—	—	434	372	301	284	319	313	376	353	333
—	523	574	525	505	495	424	385	361	411	408	501
308	359	318	327	349	319	323	295	293	322	274	—
446	476	537	521	464	—	—	—	—	—	—	—
362	430	416	398	389	383	337	352	297	314	342	338
427	477	474	476	445	478	388	335	336	358	368	389
387	455	432	431	456	411	441	489	356	367	343	370
471	438	506	525	497	489	456	430	437	426	446	462
386	394	533	492	438	412	366	335	339	314	356	400
315	314	336	330	343	344	284	290	271	278	269	296
393	383	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	413	415	390	387	343	339	298	294	297	367
307	323	380	402	400	420	386	357	323	303	273	292
282	319	370	410	400	340	318	349	351	330	320	334
298	325	310	289	275	302	281	263	265	259	261	286
260	269	287	286	266	270	262	246	255	253	243	262
245	264	294	318	310	320	312	313	285	285	275	278
—	—	—	—	—	—	—	—	—	—	—	—
272	291	304	302	306	298	279	280	277	273	274	278
239	234	250	258	251	255	254	250	251	245	242	228
274	314	338	296	292	286	308	283	287	300	342	306
—	—	—	—	317	345	353	—	400	—	—	—
345	348	346	315	335	385	490	454	478	445	396	360
—	—	—	—	—	—	—	—	—	—	—	—
413	344	398	388	—	—	—	456	484	533	467	430
340	370	391	—	—	—	—	—	540	520	500	498
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
364	347	343	267	262	269	290	—	325	331	417	428
—	—	—	—	—	—	—	—	—	432	—	—

APPENDIX III (cont.). Maximum and minimum ozone at IGY stations in 1957—1958, 10^{-3} cm

No.	Stations	Daily mean					
		1957					
		VII	VIII	IX	X	XI	XII
1	SP-6, SP-8	—	—	—	—	—	—
2	Kheis Isl.	—	—	—	—	—	—
3	Alert	294	272	282	218	231	231
4	Murchison	—	—	—	—	—	—
5	Longyearbyen	265	266	242	236	—	—
6	Resolute Bay	298	274	288	—	312	253
7	Dikson	397	328	—	—	—	—
8	Tromsö	282	281	261	207	218	163
9	Reykjavik	314	390	247	256	—	262
10	Lerwick	254	270	264	248	242	—
11	Voeikovo	355	292	296	285	286	—
12	Uppsala	285	291	286	227	216	229
13	Aarhus	316	324	315	266	248	250
14	Moscow	255	244	222	276	263	249
15	Eskdalemuir	—	—	—	262	232	262
16	Edmonton	301	276	238	239	250	246
17	Potsdam	275	288	296	267	277	310
18	Oxford	309	303	253	234	208	232
19	Moosonee	296	305	292	276	274	303
20	Uccle	280	280	245	241	318	—
21	Cambome	287	262	231	231	226	251
22	Paris (Montsouris) (midday data)	306	286	246	240	257	277
23	Caribou	—	—	—	—	—	—
24	Arosa	290	283	—	—	249	284
25	Bismarck	28—	26—	29—	21—	22—	22—
26	Green Bay	—	—	—	—	—	—
27	El'brus	—	—	—	—	—	223
28	Vladivostok	—	246	259	229	258	—
29	Sapporo	—	—	—	—	—	—
30	Alma-Ata	—	—	—	—	219	204
31	Vigna di Valle	274	299	281	264	262	281
32	Abastumani	263	251	229	247	256	270
33	Elmas	209	273	256	266	267	259
34	Washington	30—	30—	25—	27—	27—	26—
35	Messina	222	301	269	252	238	288
36	Tateno	284	265	262	247	248	284
37	Srinagar	234	246	238	—	219	224
38	Habbaniyah	272	277	277	270	267	210
39	Fort Worth	—	—	—	—	—	—
40	Kagoshima	—	—	—	—	—	—
41	Torishima Isl.	—	—	—	—	237	243
42	Quetta	186	191	205	201	197	213
43	Delhi	227	232	251	210	209	222
44	Mount Abu	224	218	222	214	202	209
45	Marcus Isl.	—	—	—	—	—	—
46	Tamanrasset (once a day)	—	—	—	192	221	162
47	Mauna Loa	—	—	—	—	—	191
48	Kodaikanal	224	234	227	231	209	212
49	Leopoldville	—	—	—	—	—	—
50	Brisbane	260	254	308	279	278	276
51	Aspendale	316	316	314	304	292	285
52	Wellington	259	290	320	291	299	259
53	Macquarie Isl.	—	—	—	—	—	—
54	Oasis	—	—	—	—	—	—
55	Port-aux-Français	—	—	—	—	—	—
56	Dumont d'Urville	—	—	—	—	—	—
57	Halley Bay	266	294	—	288	352	315
58	Little America	302	—	260	255	341	—

minima

1958											
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
—	—	—	482	395	345	285	—	—	—	—	—
—	—	500	420	358	290	246	233	—	—	—	—
250	421	453	400	369	322	310	265	275	300	388	—
—	—	—	—	357	294	282	257	—	—	—	—
—	—	—	—	—	321	287	266	264	—	—	—
—	472	458	430	389	350	313	262	291	298	342	297
—	—	—	425	506	391	259	294	—	298	—	—
248	362	419	372	359	301	265	260	256	224	220	185
255	326	357	337	342	298	300	299	269	273	215	—
—	291	334	327	354	307	294	296	257	244	206	208
—	435	421	347	321	339	317	292	283	248	240	—
214	269	397	352	308	303	292	259	241	249	209	246
269	308	384	361	336	352	319	292	271	275	242	265
270	286	364	240	290	290	326	—	285	267	260	210
269	272	362	328	354	320	308	300	272	272	238	238
264	—	398	340	333	307	304	267	268	224	288	298
300	353	—	355	291	287	286	267	243	248	—	—
245	251	337	342	352	329	324	311	270	244	232	223
300	350	345	376	361	347	324	311	284	256	275	315
—	—	313	—	317	325	317	—	250	238	234	234
263	323	289	304	318	316	293	282	248	244	219	250
263	288	339	356	313	322	288	255	259	255	209	213
—	—	—	334	310	337	272	281	253	250	256	210
269	283	333	331	337	308	299	298	263	266	246	250
281	300	340	320	327	296	306	252	255	230	248	284
—	—	329	339	314	300	249	287	240	249	376	242
257	305	323	373	251	252	185	177	200	204	216	265
—	—	—	322	284	246	233	250	246	295	248	272
—	348	386	349	342	320	295	282	274	299	267	310
271	268	268	246	271	253	229	191	197	212	246	—
288	280	330	338	309	—	—	—	—	—	—	—
276	318	328	332	248	270	363	269	251	226	245	280
281	261	288	304	307	296	255	274	275	246	283	256
296	310	288	295	310	287	292	280	255	265	244	283
292	319	259	265	243	325	302	311	285	256	278	293
287	284	318	327	308	300	287	264	265	250	246	257
254	279	250	271	279	269	258	258	242	243	213	227
270	310	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	289	262	228	306	278	245	252	255	241	256
248	254	307	311	310	301	297	277	273	234	235	328
218	228	280	278	279	279	274	275	264	261	243	264
235	246	246	221	226	235	237	228	236	230	233	250
228	220	242	243	237	243	228	226	234	214	220	228
221	226	227	248	285	288	282	273	261	261	242	225
146	155	154	191	177	148	145	172	182	186	171	166
245	240	248	270	276	271	262	262	262	257	247	242
211	215	224	237	227	240	240	237	232	233	231	212
250	240	233	230	213	234	236	239	244	239	238	234
254	253	255	—	271	258	275	302	316	306	297	313
275	273	278	260	263	336	328	317	345	342	311	286
258	251	240	242	251	261	295	290	321	322	279	227
282	282	298	308	276	366	322	330	333	368	352	310
229	306	277	—	—	—	—	—	468	468	446	—
—	—	—	—	—	—	—	—	—	—	—	—
—	190	180	150	135	150	217	200	140	120	200	200
305	278	251	244	—	232	254	—	253	275	294	334
265	282	—	—	—	—	—	—	—	285	—	—

APPENDIX III (cont.). Maximum and minimum ozone at IGY stations in 1957 –1958, 10^{-3} cm

No.	Stations	Absolute					
		1957					
		VII	VIII	IX	X	XI	XII
1	SP-6, SP-8	—	—	—	—	—	—
2	Kheis Isl.	—	—	—	—	—	—
3	Alert	287	272	271	—	229	229
4	Murchison	—	—	—	—	—	—
5	Longyearbyen	250	262	242	234	—	—
6	Resolute Bay	298	273	—	—	312	253
7	Dikson	380	319	—	—	—	—
8	Tromsö	280	280	257	204	218	163
9	Reykjavik	301	288	246	254	—	262
10	Lerwick	222	236	258	236	242	—
11	Voeikovo	317	291	285	278	272	—
12	Uppsala	285	286	286	227	216	229
13	Aarhus	282	321	303	255	245	250
14	Moscow	—	—	—	—	—	—
15	Eskdalemuir	—	—	—	242	231	—
16	Edmonton	291	271	230	239	244	246
17	Potsdam	274	283	286	259	270	310
18	Oxford	267	283	247	223	208	232
19	Moosonee	289	300	289	271	269	303
20	Uccle	274	248	245	235	308	—
21	Cambome	240	255	225	226	218	249
22	Paris (Montsouris) (midday data)	—	—	—	—	—	—
23	Caribou	—	—	—	—	—	—
24	Arosa	285	283	—	—	248	266
25	Bismarck	280	260	190	210	220	220
26	Green Bay	—	—	—	—	—	—
27	El'brus	—	—	—	—	—	220
28	Vladivostok	—	232	240	224	231	—
29	Sapporo	—	—	—	—	—	—
30	Alma-Ata	—	—	—	—	200	202
31	Vigna di Valle	217	283	274	260	192	278
32	Abastumani	250	250	204	232	256	255
33	Elmas	197	204	211	218	190	252
34	Washington	26—	29—	25—	27—	26—	26—
35	Messina	173	248	172	218	206	236
36	Tateno	263	258	248	236	240	281
37	Srinagar	234	244	238	—	219	223
38	Habbaniyah	291	272	277	270	267	210
39	Fort Worth	—	—	—	—	—	—
40	Kagoshima	—	—	—	—	—	—
41	Torishima Isl.	—	—	—	—	237	239
42	Quetta	171	179	183	190	184	192
43	Delhi	222	223	249	203	200	222
44	Mount Abu	222	218	221	213	201	209
45	Marcus Isl.	—	—	—	—	—	—
46	Tamanrasset (once a day)	—	—	—	—	—	—
47	Mauna Loa	—	—	—	—	—	183
48	Kodaikanal	218	232	227	228	204	208
49	Leopoldville	—	—	—	—	—	—
50	Brisbane	—	—	—	—	—	—
51	Aspendale	316	304	314	304	267	279
52	Wellington	—	—	—	—	—	—
53	Macquarie Isl.	—	—	—	—	—	—
54	Oasis	—	—	—	—	—	—
55	Port-aux-Francais	—	—	—	—	—	—
56	Dumont d'Urville	—	—	—	—	—	—
57	Halley Bay	—	—	—	284	348	305
58	Little America	—	—	253	255	290	—

minima												Highest maximum		Lowest minimum	
1958															
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	mean	abs.	mean	abs.
—	—	—	145	210	140	125	—	—	—	—	—	—	—	—	—
—	—	480	340	272	265	200	205	235	—	—	—	596	640	233	200
—	—	—	369	353	320	306	259	271	—	—	—	609	609	265	229
—	—	—	—	—	294	282	—	—	—	—	—	—	—	257	—
—	—	—	—	—	318	284	263	264	—	—	—	382	393	236	234
—	455	442	429	383	341	308	258	280	294	334	297	568	574	262	253
—	—	—	425	470	348	234	294	—	276	—	—	—	656	294	276
248	358	419	371	358	299	261	260	256	224	—	—	558	558	185	163
255	322	352	353	336	293	290	292	266	—	215	—	570	580	215	215
—	287	310	319	325	287	260	288	243	220	202	—	513/564	513	206	202
—	424	406	369	310	323	298	273	260	230	236	—	516	536	240	230
214	269	393	347	306	287	282	259	233	249	208	246	553	553	209	208
269	303	377	341	306	348	307	277	250	265	238	252	580	613	242	238
—	—	—	—	—	—	—	—	—	—	—	—	481	—	210	—
269	272	354	322	345	317	308	282	270	263	238	238	500	505	232	231
264	—	397	332	327	303	294	262	259	217	282	298	491	508	224	217
297	353	—	352	281	278	282	261	235	246	—	—	—	—	—	—
245	251	337	341	352	322	317	308	264	244	232	223	480	486	208	208
293	342	325	370	341	332	316	306	270	256	269	315	522	500	256	256
—	—	307	363	306	300	307	—	244	237	220	220	471	475	234	220
263	308	274	267	295	307	249	272	239	242	206	245	458	489	219	206
—	—	—	—	—	—	—	—	—	—	—	—	564	—	209	—
—	—	—	324	265	294	232	281	281	236	209	210	432	433	210	209
267	280	324	323	333	302	296	296	261	262	246	250	511	521	246	246
281	300	300	286	305	285	304	293	250	222	247	274	494	513	21—	222
—	—	266	312	314	281	235	277	236	236	—	—	457	465	240	236
238	290	274	337	223	194	175	162	186	195	204	259	448	479	177	162
—	—	—	314	281	234	215	244	239	258	244	257	—	372	229	215
—	337	363	294	322	301	290	281	252	285	266	301	573	574	267	252
233	231	250	238	219	244	189	191	177	209	216	—	326	359	191	177
280	279	321	321	303	—	—	—	—	—	—	—		—		—
256	252	304	308	234	259	254	258	244	220	225	264		—		204
258	206	169	217	212	228	199	249	238	207	258	251		477		—
296	293	287	281	277	265	250	218	247	251	231	264		455		218
245	299	216	259	218	284	284	282	228	194	244	273		525		—
284	266	318	308	300	279	265	261	252	246	246	255		533		236
250	274	250	265	275	266	258	255	242	241	213	227		344		213
267	306	—	—	—	—	—	—	—	—	—	—		—		210
—	—	—	—	—	—	—	—	—	—	—	—		—		—
—	—	276	262	228	292	270	245	252	247	238	249		415		238
236	243	304	281	301	275	291	271	264	229	231	226		402		229
193	211	256	263	264	266	258	253	246	245	232	244		410		171
235	242	238	221	221	215	237	227	235	227	230	250		325		200
228	219	230	243	235	243	228	226	231	214	218	227		287		201
216	222	221	244	275	282	280	267	254	260	238	217		318		217
—	—	—	—	—	—	—	—	—	—	—	—		—		—
234	237	246	269	274	268	260	261	261	255	244	240		304		183
210	209	221	235	227	240	239	237	231	233	230	211		258		204
222	218	222	202	190	226	223	208	232	218	206	221		338		206
—	—	—	—	259	258	275	—	308	—	—	—	400	400	253	258
275	264	254	259	256	332	322	312	338	339	302	282	475	478	260	254
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
272	269	274	298	—	—	—	322	333	351	346	301				
222	280	262	—	—	—	—	—	450	450	380	360				
—	—	—	—	—	—	—	—	—	—	—	—				
—	—	—	—	—	—	—	—	—	—	—	—				
294	268	245	244	244	225	246	—	247	269	289	327				
—	—	—	—	—	—	—	—	—	258	—	—				

APPENDIX IV. Fluctuation amplitudes of the total ozone at IGY stations in 1957—1958, 10^{-3} cm

No.	Stations	Absolute					
		1957					
		VII	VIII	IX	X	XI	XII
1	SP-6, SP-8	—	—	—	—	—	—
2	Kheis Isl.	—	—	—	—	—	—
3	Alert	48	43	28	34	80	85
4	Murchison	—	—	—	—	—	—
5	Longyearbyen	74	49	48	88	—	—
6	Resolute Bay	89	79	46	—	44	79
7	Dikson	96	108	—	—	—	—
8	Tromsö	76	48	54	157	129	188
9	Reykjavik	17	51	83	—	—	130
10	Lerwick	159	92	123	71	123	—
11	Voeikovo	64	74	68	36	18	—
12	Uppsala	80	50	68	93	115	136
13	Aarhus	128	82	78	75	106	154
14	Moscow	240	182	225	145	90	161
15	Eskdalemuir	71	58	80	98	101	130
16	Edmonton	—	—	—	89	148	93
17	Potsdam	75	115	72	64	61	8
18	Oxford	78	78	100	117	162	131
19	Moosonee	74	69	88	63	122	98
20	Uccle	48	28	110	59	30	—
21	Camborne	93	88	95	90	102	97
22	Paris (Montsouris) (midday data)	54	67	114	103	120	63
23	Caribou	—	—	—	—	—	—
24	Arosa	58	41	—	—	80	86
25	Bismarck	30	40	130	80	90	160
26	Green Bay	—	—	—	—	—	—
27	El'brus	—	—	—	—	7	74
28	Vladivostok	—	43	50	72	70	—
29	Sapporo	93	88	95	90	102	97
30	Alma-Ata	—	—	—	—	47	59
31	Vigna di Valle	116	53	63	54	89	119
32	Abastumani	29	44	58	54	40	42
33	Elmas	120	75	65	73	81	88
34	Washington	50	47	75	70	53	108
35	Messina	125	60	117	112	157	110
36	Tateno	84	40	63	58	61	72
37	Srinagar	63	35	44	—	84	63
38	Habbaniyah	33	29	22	23	46	154
39	Fort Worth	—	—	—	—	—	—
40	Kagoshima	—	—	—	—	—	—
41	Torishima Isl.	—	—	—	—	26	42
42	Quetta	55	41	40	51	46	57
43	Delhi	40	55	19	58	45	31
44	Mount Abu	18	20	19	24	32	29
45	Marcus Isl.	—	—	—	—	—	—
46	Tamanrasset (once a day)	—	—	—	61	82	80
47	Mauna Loa	—	—	—	—	—	103
48	Kodaikanal	18	7	20	12	15	17
49	Léopoldville	—	—	—	—	—	—
50	Brisbane	92	98	36	86	60	44
51	Aspendale	93	113	116	104	93	74
52	Wellington	109	93	57	93	87	89
53	Macquarie Isl.	—	—	—	—	—	—
54	Oasis	—	—	—	—	—	—
55	Port-aux-Francais	—	—	—	—	—	—
56	Dumont d'Urville	—	—	—	—	—	—
57	Halley Bay	10	8	—	93	76	78
58	Little America	74	—	147	245	121	—

amplitude												Daily mean amplitude		Individual amplitudes	
1958															
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	maximum	minimum	maximum	minimum
—	—	—	145	210	140	125	—	—	—	—	—	175	70	210	140
—	—	140	250	368	135	220	215	76	—	—	—	238	76	368	76
—	—	—	184	197	96	46	77	56	—	—	—	161	21	197	43
—	—	—	—	—	85	71	—	—	—	—	—	85	47	85	71
—	—	—	—	—	75	82	76	79	—	—	—	78	48	97	53
—	86	132	120	129	107	87	84	96	62	203	57	195	44	203	50
—	—	—	195	186	194	251	—	—	229	—	—	178	32	251	120
357	172	139	139	66	110	110	64	76	96	—	—	320	48	357	63
285	258	194	126	118	128	83	78	98	—	102	—	285	17	285	47
—	226	200	147	201	122	161	111	135	132	119	—	222	62	226	94
—	60	130	122	142	86	119	136	90	99	70	—	131	18	142	37
282	238	160	119	129	119	129	85	89	81	104	190	282	50	282	55
216	310	210	249	202	86	137	112	120	110	136	158	252	75	310	86
—	—	—	—	—	—	—	—	—	—	—	—	241	81	—	—
103	—	72	176	109	87	95	98	128	146	144	131	130	58	154	69
195	233	146	112	110	113	91	92	67	74	99	—	216	57	233	67
100	—	—	56	109	114	65	87	85	55	—	—	115	8	129	55
222	234	149	143	90	102	95	87	68	106	106	185	229	60	234	68
153	158	135	141	190	120	200	185	142	152	250	129	205	63	250	68
—	—	72	49	169	64	83	—	62	78	67	—	154	22	169	40
129	78	194	212	194	107	142	99	143	108	160	205	200	49	230	78
—	—	—	—	—	—	—	—	—	—	—	—	321	54	—	—
—	—	—	92	168	129	158	150	246	122	162	228	201	80	228	92
185	232	193	193	170	101	87	56	76	89	58	103	222	41	232	51
125	177	178	183	111	255	142	211	263	160	141	130	177	30	255	30
—	—	199	130	91	135	120	66	98	101	—	—	145	34	199	66
141	105	190	121	256	220	168	155	87	93	115	—	213	7	256	22
—	—	—	120	91	67	69	75	74	118	109	76	81	43	120	57
119	77	194	212	194	107	142	99	143	108	160	205	200	86	212	99
75	128	68	89	130	75	134	104	116	113	58	—	104	0	130	58
166	197	216	200	161	118	94	59	68	126	90	141	190	34	216	59
106	178	112	90	155	124	83	94	53	94	117	64	121	29	178	47
169	271	305	259	233	250	189	86	98	151	109	138	195	34	305	86
91	162	145	150	179	146	191	271	109	116	112	106	137	47	271	60
226	139	290	266	279	205	172	148	209	232	202	189	241	42	290	139
102	128	215	184	138	133	101	64	87	68	110	145	186	40	215	64
65	40	86	65	68	78	26	35	29	37	56	69	84	24	84	26
126	77	—	—	—	—	—	—	—	—	—	—	154	22	154	22
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	137	153	162	95	73	94	46	47	59	118	143	29	162	46
71	80	80	121	99	145	95	86	59	74	42	66	91	25	145	31
126	136	114	147	136	74	60	96	105	85	88	90	115	23	147	60
63	83	72	68	54	87	44	36	31	30	32	36	66	19	87	26
32	50	57	43	31	27	34	20	24	39	25	35	48	18	57	20
29	42	73	74	35	38	32	46	31	25	37	61	64	19	73	29
—	—	—	—	—	—	—	—	—	—	—	—	119	54	—	—
30	19	19	16	—	—	—	—	—	—	—	—	103	12	116	16
29	25	29	21	24	15	15	13	20	12	12	17	26	7	34	12
52	96	116	94	102	60	85	75	55	82	136	85	49	15	136	52
—	—	—	—	56	87	78	—	92	—	—	—	98	44	92	56
70	84	92	56	79	53	168	142	140	106	94	78	146	41	168	53
—	—	—	—	—	—	—	—	—	—	—	—	110	52	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
141	75	124	90	—	—	—	134	151	182	121	129	154	56	182	75
113	90	129	—	—	—	—	—	90	70	120	132	85	2	132	70
—	—	—	—	—	—	—	—	—	—	—	—	330	80	—	—
70	79	98	23	18	44	44	—	78	62	128	101	108	8	128	18
—	—	—	—	—	—	—	—	—	174	—	—	245	31	252	154

APPENDIX IV. Fluctuation amplitudes of the total ozone at IGY stations in 1957—1958, 10^{-3} cm

No.	Stations	Daily mean					
		1957					
		VII	VIII	IX	X	XI	XII
1	SP-6, SP-8	—	—	—	—	—	—
2	Kheis Isl.	—	—	—	—	—	—
3	Alert	62	58	43	—	82	87
4	Murchison	—	—	—	—	—	—
5	Longyearbyen	97	55	53	90	—	—
6	Resolute Bay	99	89	—	—	50	79
7	Dikson	124	120	—	—	—	—
8	Tromsö	78	63	63	174	129	188
9	Reykjavik	47	94	95	—	—	130
10	Lerwick	191	134	203	94	124	—
11	Voeikovo	117	91	79	74	37	—
12	Uppsala	80	55	68	100	115	136
13	Aarhus	178	95	127	101	126	174
14	Moscow	—	—	—	—	—	—
15	Eskdalemuir	85	69	88	107	107	154
16	Edmonton	—	—	—	101	154	93
17	Potsdam	76	129	84	81	70	—
18	Oxford	135	116	115	131	162	131
19	Moosonee	101	83	95	68	131	98
20	Uccle	55	61	111	84	40	—
21	Cambome	230	138	114	115	120	99
22	Paris (Montsouris) (midday data)	—	—	—	—	—	—
23	Caribou	—	—	—	—	—	—
24	Arosa	63	51	—	—	81	107
25	Bismarck	30	40	130	80	90	160
26	Green Bay	—	—	—	—	—	—
27	El'brus	—	—	—	—	22	77
28	Vladivostok	—	57	80	88	107	—
29	Sapporo	170	138	114	115	120	99
30	Alma-Ata	—	—	—	—	78	89
31	Vigna di Valle	186	97	77	83	204	137
32	Abastumani	53	53	95	86	47	71
33	Elmas	174	177	163	216	172	148
34	Washington	90	60	100	80	60	120
35	Messina	254	179	238	227	219	194
36	Tateno	116	75	92	80	85	81
37	Srinagar	71	43	48	—	84	64
38	Habbaniyah	33	29	22	23	46	154
39	Fort Worth	—	—	—	—	—	—
40	Kagoshima	—	—	—	—	—	—
41	Torishima Isl.	—	—	—	—	31	58
42	Quetta	89	107	112	89	62	90
43	Delhi	45	64	26	68	52	36
44	Mount Abu	20	20	20	25	37	29
45	Marcus Isl.	—	—	—	—	—	—
46	Tamanrasset (once a day)	—	—	—	—	—	—
47	Mauna Loa	116	38	54	58	70	32
48	Kodaikanal	34	12	30	16	20	22
49	Leopoldville	—	—	—	—	—	—
50	Brisbane	—	—	—	—	—	—
51	Aspendale	93	125	116	115	178	91
52	Wellington	—	—	—	—	—	—
53	Macquarie Isl.	—	—	—	—	—	—
54	Oasis	—	—	—	—	—	—
55	Port-aux-Francais	—	—	—	—	—	—
56	Dumont d'Urville	—	—	—	—	—	—
57	Halley Bay	—	—	—	103	91	93
58	Little America	—	—	154	252	198	—

amplitude

1958											
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
—	—	—	80	175	70	70	—	—	—	—	—
—	—	76	99	238	86	152	142	—	—	—	—
—	45	154	152	161	88	37	54	47	43	21	—
—	—	—	—	47	85	71	39	—	—	—	—
—	—	—	—	—	61	78	70	76	—	—	—
—	69	90	119	82	83	69	69	85	56	195	57
—	—	—	169	120	88	178	32	—	134	—	—
3	168	139	138	65	106	106	62	76	96	145	215
285	244	160	114	89	108	69	70	95	90	98	—
—	222	171	125	110	91	96	62	84	100	110	89
—	41	95	69	131	60	70	83	67	55	66	—
282	238	156	106	127	103	119	85	101	81	103	90
206	252	196	207	105	80	104	90	87	88	125	140
152	138	98	241	190	80	128	—	81	103	65	130
103	—	70	151	84	77	77	81	99	130	126	122
195	216	138	106	101	89	88	59	57	64	99	163
96	—	—	48	92	99	58	77	71	49	—	—
222	229	136	133	90	88	82	65	60	98	106	185
136	141	115	124	161	94	76	88	85	136	205	122
—	—	66	—	154	32	66	—	56	76	22	—
129	49	141	154	112	74	91	77	96	86	145	200
271	276	170	157	125	113	100	116	78	64	184	321
—	—	—	80	122	86	109	118	116	106	115	201
175	222	174	180	57	91	82	54	69	85	88	103
101	177	87	149	82	172	94	95	134	143	128	100
—	—	128	86	85	89	97	47	88	84	34	145
66	46	115	44	213	124	146	103	49	76	94	—
—	—	—	81	81	32	41	48	54	48	78	30
129	149	141	154	112	74	91	77	96	86	145	200
23	58	78	62	42	50	63	104	82	59	0	—
156	190	187	159	140	85	72	34	46	108	82	129
69	104	54	49	121	110	48	72	39	78	66	43
96	195	188	99	107	76	109	39	34	75	66	133
70	113	137	120	98	111	87	154	70	91	81	70
179	108	194	241	176	83	109	42	77	130	112	125
87	94	186	118	102	81	62	63	60	55	100	138
57	29	84	55	57	69	24	31	29	35	56	69
120	69	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	93	143	126	67	56	63	40	29	56	85
52	66	60	91	74	89	62	64	28	58	25	58
78	113	69	90	115	50	18	25	23	54	67	57
61	66	63	65	40	63	39	32	26	27	26	36
26	48	42	33	24	23	34	20	21	36	23	34
22	33	53	64	21	25	24	27	19	22	26	46
54	91	119	116	75	62	57	73	—	56	82	51
21	33	45	38	29	26	16	17	12	—	—	—
23	15	26	19	24	14	12	13	19	11	10	15
15	31	39	34	47	21	23	16	22	32	51	49
70	52	52	—	46	87	78	56	84	69	46	25
59	67	56	51	65	41	146	118	130	103	85	61
104	56	52	56	74	110	92	99	71	87	87	103
—	—	—	—	—	—	—	—	—	—	—	—
124	56	83	80	111	63	126	126	141	154	96	110
85	50	83	—	—	—	—	—	60	40	2	62
—	80	180	280	254	310	213	100	165	300	330	130
53	58	90	20	—	37	27	—	65	53	108	85
108	31	—	—	—	—	—	—	—	107	—	—

APPENDIX V. Ozone amount in Moscow in 1934—1935, 10^{-3} cm

Month	1934			1935		
	mean	maximum	minimum	mean	maximum	minimum
February	432	487	352	317	—	—
March	431	479	406	385	467	342
April	—	—	—	458	493	409
May	423	456	383	440	491	382
June	394	447	358	404	481	348
July	374	482	317	389	443	342
August	359	443	328	358	416	324
September	355	385	333	348	382	328
October	—	—	—	241	—	—

EXPLANATORY LIST OF ABBREVIATIONS OF USSR INSTITUTIONS AND PERIODICALS APPEARING IN THIS BOOK

Abbreviation	Full name (transliterated)	Translation
AN SSSR	Akademiya Nauk SSSR	Academy of Sciences of the USSR
DAN SSSR	Doklady Akademii Nauk SSSR	Proceedings of the Academy of Sciences of the USSR
GGO	Glavnaya Geofizicheskaya Observatoriya [im. A.I. Voeikov]	The A.I. Voeikov Main Geophysical Observatory
MGG	Mezhdunarodnyi Geofizicheskii God	International Geophysical Year
MGS	Mezhdunarodnoe Geofizicheskoe Sotrudnichestvo	International Geophysical Collaboration
MGU	Moskovskiĭ Gosudarstvennyi Universitet	Moscow State University